Energy Management and Power System Operation Vol 6

Elisabeth Drayer

# Resilient Operation of Distribution Grids with Distributed-Hierarchical Architecture

Energiemanagement und Betrieb elektrischer Netze
Fraunhofer IEE
KDEE Kompetenzzentrum für Dezentrale Elektrische Energieversorgungstechnik

# Energy Management and Power System Operation

Vol. 6

Edited by
Prof. Dr.-Ing. Martin Braun
University of Kassel

Elisabeth Drayer

# Resilient Operation of Distribution Grids with Distributed-Hierarchical Architecture

kassel
university
press

This work has been accepted by the Faculty of Electrical Engineering / Computer Sciences of the University of Kassel as a thesis for acquiring the academic degree of Doktor der Ingenieurwissenschaften (Dr.-Ing.).

Supervisor: Prof. Dr.-Ing. Martin Braun
Co-Supervisor: Dr. Raphaël Caire

Defense day: 29th June 2018

Bibliographic information published by Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at http://dnb.dnb.de.

Zugl.: Kassel, Univ., Diss. 2018
ISBN 978-3-7376-0592-2 (print)
ISBN 978-3-7376-0593-9 (e-book)
DOI: http://dx.medra.org/10.19211/KUP9783737605939
URN: https://nbn-resolving.org/urn:nbn:de:0002-405935


www.upress.uni-kassel.de

Printing Shop: Print Management Logistics Solutions, Kassel
Printed in Germany

# Zusammenfassung

Diese Dissertation beschäftigt sich mit dem Design und der Implementierung einer resilienten Netzbetriebsführung für das Verteilnetz. Die Motivation dafür ist ein Fortschreiten der Dekarbonisierung, Dezentralisierung und Digitalisierung im ganzen Energiesektor, besonders aber im Verteilnetz. Diese Veränderungen transformieren das bisher passive Verteilnetz in ein System das eine aktive Betriebsführung besitzt. Unter dem Begriff „Resilienz“ werden dabei Fähigkeiten eines Systems verstanden, mit Fehlern und Störungen umzugehen und diese zu absorbieren, sich ihnen anzupassen und sich davon zu erholen.

Im Falle der hier entwickelten Netzbetriebsführung ist die Resilienz leitendes Designprinzip, einerseits bei der Wahl der Architektur, andererseits bei der Wahl der Methoden für die Betriebsführung. Auf Architekturebene entwickelt diese Arbeit eine verteilte-hierarchische Kontrollarchitektur für die Realisierung der Betriebsführung. Im Gegensatz zu klassischen zentralen Ansätzen entsteht die Netzbetriebsführung durch das Zusammenwirken geographisch verteilter Aktoren. Jeder der Aktoren erfüllte eine bestimmte Rolle und überwacht und steuert ein begrenztes geographisches Gebiet (z.B. das Netzgebiet eines Mittelspannungsabgangs). Diese Aktoren können sowohl horizontal (verteilt) als auch vertikal (hierarchisch) interagieren. Diese Arbeit zeigt, dass solch eine verteilte-hierarchische Architektur eine valide Realisierung für Betriebsführungen im Verteilnetz darstellt. Anhand einer Resilienzanalyse wird die gesteigerte Resilienz im Vergleich zu anderen Architekturen von Betriebsführungen herausgearbeitet.

Für diese verteilte-hierarchische Architektur wurden Methoden entwickelt, welche die Architektur optimal ausnutzen und einen vollautomatischen Betrieb des Verteilnetzes ermöglichen. Dazu wurde eine heuristische Optimierung entwickelt, die als vielfältiges Werkzeug genutzt wird um Probleme wie Spannungsbandverletzungen oder Überlastungen zu lösen. Optimiert wird dabei der Einsatz von Flexibilitäten, die von steuerbaren Lasten, Speichern und Erzeugungsanlagen, aber auch vom Netz selbst, stammen. Es wird gezeigt, dass diese heuristische Optimierung bei gleichwertigen Lösungen im Vergleich zu klassischen Optimierungsmethoden robuster und flexibler eingesetzt werden kann.

Eine weitere wichtige Methode, besonders unter dem Blickwinkel der Resilienz, ist das Selbstheilen (engl. self-healing) des Netzes. Diese Methode kommt bei strangförmig betriebenen Mittelspannungsnetzen zur Anwendung, nachdem ein Netzfehler zu einem dauerhaften Ausfall von Abgängen führt. Nach der Lokalisierung des Fehlerorts werden die Schaltstellungen der fernwirkbaren Schalter so optimiert, dass größtmögliche Teile des Netzes wieder versorgt werden können. Für den in dieser Arbeit entwickelten Ansatz wird die verteilte Architektur der Netzbetriebsführung ausgenutzt und der Lösungsraum, so weit notwendig, iterativ erweitert. Dies ermöglicht es, sehr schnell eine ausreichend gute Lösung für das komplexe kombinatorische Problem zu finden.

Die entwickelten Ansätze und Methoden wurden nicht nur theoretisch beschrieben sondern in Simulationen und in einem Feldtest umgesetzt. Dies erhöht den Reifegrad der hier entwickelten Technologien und macht ihre Relevanz für die praktische Anwendung deutlich.

# Abstract

This thesis is about the design and the implementation of a resilient grid operation for the distribution grid. This research question is induced by the advancing of three trends: Decarbonisation, decentralisation and digitalisation. These three trends affect the whole energy sector, but especially the electrical distribution grid. They transform the hitherto passive distribution grid into an active system that contains an active operation. The term "resilience" describes capabilities of the system to absorb, to adapt, and to recover from faults and disturbances.

For the grid operation developed in this thesis, resilience is the leading design principle. This is realised on the one hand with the choice of the operation architecture, on the other hand for the choice of possible methods and functions. This thesis develops a distributed-hierarchical operation architecture. In contrast to classic central approaches, the grid operation is realised by the interaction of geographically distributed entities. Each of these entities fulfils a certain role and supervises and controls a limited geographical area (e.g. the grid area belonging to a medium voltage feeder). These actors can interact horizontally (distributed) with equivalent actors, as well as vertically (hierarchical) with higher-level and lower-level actors. This thesis shows that such a distributed-hierarchical operation architecture is a valid realisation for a grid operation in distribution grids. The increased resilience of such a grid operation architecture compared to other architectures is validated by means of a resilience analysis.

For this distributed-hierarchical architecture several methods have been developed that optimally benefit from the operation architecture and that allow the fully automated operation of the distribution grid. For that purpose a heuristic optimisation has been developed that can be used as multi-purpose tool to solve problems like voltage profile violations and congestions. Subject of the optimisation is the use of flexibilities that are provided by controllable loads, storage, and distributed generators, but also by the grid itself. The work of this thesis shows that this heuristic optimisation provides solutions equivalent to classic optimisation approaches while at the same time it is more robust and flexible.

Another important method, especially with regard to resilience, is the self-healing capability. This method is used in radially operated medium voltage grids if a fault leads to a permanent outage of feeders. After the fault is localised, the self-healing method optimises the switch settings to resupply as many clients as possible. For the approach developed in this work, the distributed architecture of the grid operation is used and the search space is evolvingly enlarged. For the complex combinatorial problem, this allows a fast identification of possible solutions.

The approaches and methods developed in this thesis are not only described theoretically but are implemented and tested in simulation and in a field test. This increases the readiness level of the technologies and highlights its relevance for the practical application.

# Contents

# PART I

# INTRODUCTION

CHAPTER 1

# The Future of the European Power System

The “Energy 2020” strategy of the European Commission [1] starts with the very lively words: “Energy is the life blood of our society. The well-being of our people, industry and economy depends on safe, secure, sustainable and affordable energy.” As the European Commission is rather known for its dry and bureaucratic language and communications than for attention-grabbing headlines, this expressive sentence must indicate that they really want to emphasis its message. Energy in this context means the overall energy consumption of our society, including the three main areas: electricity, heating, and mobility. The here presented work focuses on the electricity sector. This is in line with the expected development of this sector: Its importance will only increase in the years to come [2].

The infrastructure that provides our society with electricity is the power system. Its structure is introduced in Section 4.1. For long years, this system and the interaction of its components was a very solid and steady system. Efforts like the liberalisation of the energy markets fundamentally changed the business models and structure of the involved companies. However, the technical and operational principles of the grids stayed quite the same [3]. But this has changed: the power system in Europe is currently undergoing fundamental transformations. The ways in which these transformations are taking place can be summarised by the “3Ds”: decarbonisation, digitalisation and decentralisation.

These three movements are further described in the following three sections. These transformations result in considerable challenges. Challenges that can not be overcome by planning and operating the power system as we did the last 30 years ago. Challenges that force us to substantially re-design our system. Thus, this introduction ends with an overview over major challenges that must to be addressed and that require major efforts for research, industry and the society as a whole. These challenges must be met. To use again the words of the Energy 2020 document: “The price of failure is too high.” [1].

## 1.1 Decarbonisation

The term “decarbonisation” refers to the transformation of the economy with regard to the reduction of greenhouse gas emissions, especially of carbon dioxide ($CO_2$). For the energy industry the aim is to reduce the dependency on fossil energy carriers like oil, coal and gas and to attenuate the effect of the human induced climate change. Following several previous negotiations and agreements, the 21th United Nations Climate Change Conference was held in Paris at the end of 2015. This conference resulted in the Paris Agreement that aims to limit the increase of the global average temperature to 1.5 °C (above the reference temperature of pre-industrial level) [4]. One of the main parameters humanity can control with regard to this goal is the emission of greenhouse gases.

Two main approaches to achieve this goal is to increase the energy efficiency and rise the share of electricity produced by renewable sources [1], [5], [6]. The decarbonisation of the mobility sector will mostly result in electric vehicles [5]–[7].

## 1.2 Digitalisation

Digitalisation is a general trend that is influencing nearly all aspects of our live. And the power system is no exception. The term describes the increasing penetration of our economy and society with information and communication technology (ICT). A prominent aspect of the digitalisation of the power system is the roll-out of intelligent metering systems [8]. But it is much more than that. The European Technology Platform SmartGrids defines the digitalisation of the energy system as: "The process of implementing and operating a set of assets by monitoring, transferring and analysing data which have been generated by one of the actors in the energy system" [9].

## 1.3 Decentralisation

The increasing decentralisation of the power systems results partly as a side effect of the two transformations mentioned above. A major step for the decarbonisation in Germany was the valorisation of renewable energies [10]. This led to an increased installation of small scale generators, especially wind generators and photovoltaic (PV) systems, mainly connected to the distribution grid. The digitalisation provides the possibility to establish demand side management (DSM) capabilities even on the lowest voltage level. Demand side management is seen as a solution to balance the power system in the presence of the majoritarian volatile generation of renewable energies. It will be especially effective with the increasing penetration of electric vehicles and charging stations.

Thus, on the one hand, an increasing number of small scale generators or controllable loads is introduced in the grid, leading to a decentralised system. On the other hand, large power plants that nowadays carry the principal responsibility for the stability of the power system are shut down. This has partly economic reasons, partly results from laws that force the nuclear power phase-out to be realised in the next years [11]. This trend increases decentralisation even more.

## 1.4 Challenges for the Distribution Grid

The above mentioned "3D" transformations result from political will, scientific progress and the necessity to cope with the demands of our society. But they lead to considerable challenges. In accordance to the sections above, these challenges are sorted according to the "3D", and summarised in Table 1.1. The work of this thesis focuses on the distribution grid, so the following challenges are especially related to the distribution grid. Very important for the welfare of our society will be the question of social implications that result from the above mentioned transformations. Especially the digitalisation will tremendously change the way we work and live. But this is outside the scope of the here presented work and must be addressed not only from a research perspective but also by legislation.

### Decarbonisation

In Europe, the large scale integration of renewable energy resources mainly increases the photovoltaic and wind based generation. In Germany, other renewable sources like hydro power,

Table 1.1: List of challenges that arise from the “3D” transformations.

| Decarbonisation | Digitalisation | Decentralisation |
|---|---|---|
| Volatile energy supply through renewable energies<br>Increasing loads in the distribution grid through charging stations of electric vehicles | Large amounts of measurements and data that need to be treated and communicated<br>Risk of software and hardware errors<br>Increasing interdependence between IT and power system<br>Cyber attacks | Extensive electricity feed-in in the distribution grid<br>Increasing number of generators and controllable loads |

geothermal energy or biomass production have only limited installation capability that are economically beneficial or are limited by the land consumption [12, p. 35-42]. But photovoltaic and wind energy depend on meteorological conditions. Their contribution to the overall energy demand varies significantly from one point in time to another. The decarbonisation of the mobility sector results in an increasing number of electric vehicles. Their large scale charging in domestic homes will bring the distribution grids in certain regions to their limits, or at least change the traditional load patterns on feeders, presumably increasing the already high evening peak load when everybody gets home.

## Digitalisation

One major effect of the digitalisation is that processes are related to huge amounts of digital information, data and measurements. The effective use of this data is often related to the buzzword “big data”. But to be able to benefit from it, efforts must be made to handle and process the increasing amount of data. This is especially important for high-resolution measurements of customer consumption, as they are very sensible with regard to privacy issues [13, p. 8].

Historically the power systems is characterised by long term investments and devices that are very robust and operational for several decades. But the digitalisation introduces new types of devices into the power system. Devices designed for IT purposes are seldom used more than a couple of years and compared to classic grid devices they are rather error-prone. The situation is even worse for the software that runs on the new devices. Errors of different types and with different impact that originate from flawed and broken software will increase.

Aside from these unintentional errors, the targeted attack of power systems using IT and communication systems is a new and increasing threat [14]. The danger of cyber attacks on power system infrastructure has to leave the attention grabbing corner of fictional thrillers to be evaluated and treated according to security standards.

Attention must be paid to the vulnerabilities that are created by strongly coupling the power system with an ICT system. Disturbances or failures in one system can lead to cascading failures between interdependent systems [15].

## Decentralisation

Almost three-quarters of renewable generators are connected to the low and medium voltage grid (status: end 2015, calculated based on figures of [16][1]). In its origins, the distribution grid was not constructed for this massive feed-in. Voltage problems and congestions appear. And with an even increasing penetration of small-scale renewable energies and the shut-down of bulk power generators, system stability becomes an issue. Currently, the transmission system operators (TSOs) use almost exclusively ancillary services provided by generators on the extra high voltage level to stabilise the grid. In a long term perspective, distributed generators must be able to contribute to the ancillary services and take over the role of the bulk generators. While the first issue of this paragraph, congestions and voltage problems, could be overcome with classic grid reinforcements, the provision of ancillary services needs an active control mechanism.

[1] This number only considers renewable generators that are billed according to the EEG feed-in remuneration.

# CHAPTER 2

# Resilient Design of the Power System

To keep up with the transformations and to overcome the resulting challenges described in Chapter 1, the power system needs to be redesigned. Basis for this redesign is the grid structure presented in Section 4.1. This chapter starts a short survey on major considerations on how to design the power system of the future. Then the concept of "resilience" as major design principle is introduced in Section 2.2. This includes a closer look on the definition of resilience and the capabilities that characterise resilient systems. A review on research focussing on resilience in power systems is given in Section 2.3. Section 2.4 summaries the resilience functions considered for the work of this thesis.

## 2.1 New System Design

One of the most considered ideas of a new system design for the power system has a famous name: It is called the "smart grid". This name is rather a slogan than a precise definition, although several recommendations have been made by various institutions. In the European context the definition of the European Technology Platform SmartGrids should be mentioned:

> "A SmartGrid is an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies." [17]

But how this smart grid actually needs to be designed is an ongoing debate. The power system design proposed by Amin and Wollenberg in [18] aims for an extensive introduction of information technology and distributed intelligence into the power system. This is done to realise a robust, adaptive, and reconfigurable grid operation for the transmission level. They claim: "The best minds in electricity [research and development] have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming — and interconnected with everything else." The article demands "plug-and-play" capabilities for every new device installed in the grid (e.g. a new circuit breaker).

The concept described by Farhangi in [19] focuses on a new system design for the distribution grid. He sees the development towards this new power grid as an evolutionary and organic process where different ways to operate the grid will coexist. For him, "the smart grid is therefore expected to emerge as a well-planned plug-and-play integration of smart microgrids that will be interconnected through dedicated highways for command, data, and power exchange."

Another famous and new system design is proposed by the project "Vision of Future Energy Networks" [20]. The key idea is to develop a new design not only for the power system but to combine the different energy infrastructures (e.g. electricity, gas, heating) and to consider them together. From this research resulted the concept of "energy hubs", the units where energy is converted and stored from one carrier to another, and "energy interconnectors", a way to transport different forms of energy together.

A last new design, that has been discussed controversial in the last years in Germany is the "Zellulare Ansatz" (the cellular approach). Its key idea is to balance energy consumption and energy generation as low-level as possible. The lowest level of this system is the so called "cell" that can be a household, industry or a part of a low voltage grid [21]. This concept it placed between the concepts proposed in [19] and [20], going in the direction of microgrids (but allowing the exchange between cells and not pushing for an isolated operation) and considering all energy carriers together.

For the author of [19], "the smart grid is required to be self-healing and resilient to system anomalies." These are two concepts that are at the heart of this thesis. While self-healing is treated further on in Chapter 10, the concept of resilience and its application on infrastructures like the power system is introduced in the following sections.

## 2.2 Infrastructure Resilience

The term "resilience" used in engineering classically refers to the specific energy a material absorbs when it is elastically strained [22]. It is thus a term of material science. Other fields where the term resilience is used are psychology, ecology, economy and industrial safety [23], [24]. The general direction of the term "resilience" is quite the same for all these domains, but with subject-specific aspects. Thus, Section 2.2.1 introduces several definitions of resilience, especially important for the following elaborations. To distinguish the concept of resilience from related ideas, Section 2.2.2 gives some clarification. Characteristic capabilities of resilient infrastructures are introduced in Section 2.2.3.

### 2.2.1 Definition of Resilience

When investigating systems, the term "resilience" was first used by Hollinger to describe the property of ecological systems to be able to absorb disturbances [25, p. 14].

Faced with unseen acts of terror and large scale natural disasters, the U. S. administration started to investigate resilience concepts to secure their critical infrastructures over a decade ago [26, p. 75f]. The term critical infrastructure includes all the public infrastructures like transport, health care system, and communication. But one of the most important infrastructures, as almost all other critical infrastructures depend on it, is the power system. From this context comes the following definition of resilience for infrastructures, proposed by the National Infrastructure Advisory Council:

> "Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event." [27, p. 8]

In the first sentence, this definition gives a direction on how resilience could be measured. It further on introduces a list of verbs that describe the capabilities of resilient systems. These capabilities are discussed in Section 2.2.3.

The desired behaviour of most of the critical infrastructures depends substantially on the control system that is operating it [28]. The following resilience definition focuses on the control system part of the infrastructure:

> "A resilient control system is one that maintains state awareness and an accepted level of operational normalcy in response to disturbances, including threats of an unexpected and malicious nature." [28]

The same focus is taken in this thesis. As it concentrates on the resilience of the grid operation, it leaves aside questions that deal with the resilience of the components of the power system, like which type of electricity pylon has the best resilience properties.

Depending on the complexity, a control system is often realised as a computing system. Laprie combines in [23] the term "dependability" with resilience and derives that for computing systems resilience is

> "[...] the persistence of dependability when facing changes." [23]

All the above given definitions plastically describe the concept of resilience. But they face difficulties when applied to assess resilience quantitatively. The authors of [26] propose a definition especially designed to allow the assessing and quantification of resilience:

> "Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system-performance levels." [26, p. 107]

Like the definition of the National Infrastructure Advisory Council, this definition gives two major indicators for the resilience of a system: the reduction of the duration and magnitude of disruption.

### 2.2.2 Resilience and Related Concepts

The concept of resilience is related to other concepts common in engineering and computer systems. For example in computer systems, resilience is often used as a synonymy for "fault-tolerant" [23].

Related but nevertheless different to resilience is the concept of "robustness". The latter is not used consistently in literature. In [29] "robustness" has to do with the magnitude of the tolerable degree of disturbance. In [26, p. 6] robustness is a characteristic of protection systems that prevent disturbances. And in [23] the term "robustness" is used to describe a computing system that "retains its ability to deliver service in conditions which are beyond its normal domain of operation". Resulting from this inconsistency, the term robustness is not used in this thesis.

Another related concept is "protection". The protection of critical infrastructures should minimise or prevent undesired consequences [26, p. 4]. Protection can be seen as the solution against disturbances with rather high probability but low impact. In power system, protection generally refers to the concepts that are applied to prevent persistent abnormal currents that might destroy components. So the classic power system protection can not prevent the failure in a particular component but minimises the effect on other devices in the power system.

To define the necessary level of protection, generally a risk assessment is conducted. The leading equation to evaluate the risk $R_e$ of a certain event $e$ is given as

$$R_e = P_e \cdot SF_e \cdot C_e, \tag{2.1}$$

with $P_e$ the probability that the event $e$ happens, $SF_e$ the probability that the system will fail due to event $e$ and $C_e$ the consequences that might result [26, p. 5]. The problem is that standard probability theory and statistics reach their limits when considering non-random events but deliberate actions or low-probability high-impact events [26]. Additionally, especially in extensive and complex systems with a lot of very different possible attack vectors, protection is not possible or affordable everywhere. This is when resilience steps in.

The authors of [29] describe it in the following way: "Resilience [...] is not about preventing failures but in managing how the system behaves during failure and recovery." Seen from this perspective, resilience is related to classic engineering principles like the fail-safe or fail-secure approach [30, p. 45]. A fragmentary idea to visualise the relation between protection and resilience is given in Fig. 2.1. Protection can be seen as a shell to prevent disruptions from destroying the system. Inspired by the origin of the word resilience in material science, resilience can be seen as springs that stabilise the system even if a disruption affects the system. Thus a secure system includes always a combination of protection and resilience, leading to the following relation

$$\text{secure systems} = \text{protection} + \text{resilience}.$$

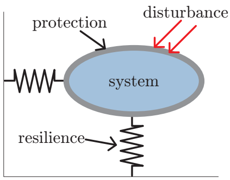



Figure 2.1: Drafted relation between protection (shell) and resilience (springs).

### 2.2.3 Capabilities of Resilient Systems

The resilience definition proposed in [27, p. 8] and cited above, gives a list of verbs that describe necessary abilities of resilient infrastructures: to anticipate, to absorb, to adapt and to recover from a disruptive event. As this work focuses on the behaviour of systems after a disruptive event has occurred, the first ability "to anticipate" is omitted here. This is in line with major previous research on resilience [26, p. 116ff], [31]. So the three categories of resilient capabilities are: absorptive, adaptive and restorative capabilities. In response to a disturbance these three categories are generally triggered in a temporal order, see Fig. 2.2. This figure visualises the evolution of the system performance $SP$ after a disturbance.

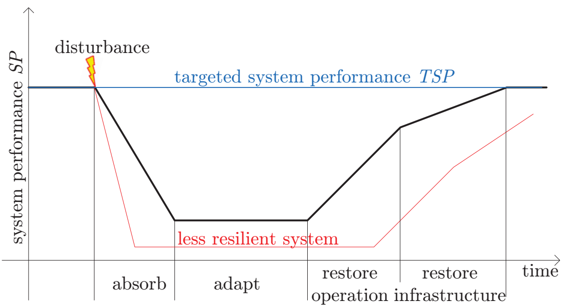



Figure 2.2: Schematic behaviour of the system performance of a resilient system (black) compared to a less resilient system (red); based upon [26], [32], [33].

A disturbance leads to a decrease of the system performance $SP$ and a deviation from the targeted system performance $TSP$. In the context of power systems, the number of supplied clients is often used to measure the system performance. In the phase directly following the disturbance the system tries to **absorb** the negative effects of the disturbance. The perturbations in the system that result from the disturbance are minimised [26, p. 117f]. The same source gives a general list of possible resilience enhancing concepts for this phase: redundancy (duplication of components), segregation (separating of major functions of an infrastructure so that disturbances can not cascade), and robustness (strengthening of protection).

In the second phase after a disturbance, the system **adapts** to the degraded situation. For this, the system moves to non-standard operation modes that normally would not be used because of lower efficiency or higher costs [26, p. 117f]. But in the degraded situation these exceptional operation modes can help to augment the system performance. Possible resilience enhancing concepts according to [26, p. 120] are: substitution (replacing of resources), rerouting (choosing alternative paths), reorganisation (changing the operation or organisation mode). The human creativity and flexibility is another important aspect of resilience and especially difficult to imitate when realising resilient technical systems.

The last phase is characterised by attempts to **restore** the system. As indicated in [34], for some systems (including the power system) one can distinguish between operational and infrastructural restoration. Operational restoration aims to restore the system performance without necessarily repairing possible damaged components. Infrastructural restoration on the other hand really treats the physical restoration of the infrastructure, e.g. the replacing of damaged material. An example of a resilience enhancing concept for the latter is to hold available spare and replacing material.

## 2.3 Resilience in Power System

The research on resilience in the context of power systems had, until recently, a strong focus on natural disasters [35]. Only lately, aspects like man-made attacks (on a software or hardware basis) are also considered [33], e.g. the resilience of the power system against false data injection attacks [36]. This is the reason why in literature about power system resilience, resilience is generally considered to be exclusively an approach against high-impact, low-probability disturbances. As motivated in the introduction in Section 1.4, the increasing interdependence between power and ICT infrastructure affects the resilience of the combined system fundamentally. It requires new approaches to assess the security and resilience of the two interconnected systems [37]. As already introduced in the previous section, in the power system one can distinguish between operational and infrastructural resilience [34]. Operational resilience describes capabilities that aim at the functional aspects of the power system. Thus operational resilience helps to re-establish the service. Infrastructure resilience on the other hand refers to capabilities that increase the resilience from a component point of view. For a grid that suffers from a permanent fault, e.g. a damaged line, operational resilience tries to resupply the clients, while infrastructural resilience aims at the repairing of the damaged line. This distinction is important when it comes to resilience measures that might be able to resupply clients without repairing possible damages in comparison to resilience measures that facilitate the repair of destroyed components. The first method enhances the operational resilience and the second the infrastructural resilience.

According to the above motivated distinction between operational and infrastructural resilience, also the methods to enhance resilience capabilities can be divided. Panteli and Mancarella give in [32] an example list of possible measures to increase the infrastructure resilience especially with regard to extreme weather events. This lists includes: the switching from overhead lines to underground cables, redundancy in lines and the rerouting of power lines through areas less affected by severe meteorological disturbances. These measures are also referred to as "hardening" measures [32]. For the enhancement of the operational resilience the authors suggest the distribution of energy resources and control, the use of microgrids, adaptive protection schemes, situation awareness of the control system and risk management approaches. These methods are called "smart" methods [32]. The authors of [33] follow a comparable approach, adding to the operational resilience aspects like the resupply of loads after faults and demand side management.

The report "Das Energiesystem resilient gestalten" (resilient design of the energy system) [38] presents resilience strategies against a list of possible vulnerabilities. These counter actions that focus on the resilience of the power system are not only technical but include organisational and social perspectives and consider concepts like: monitoring, participation and information of the society, flexibility of resources, diversification, redundancies, storage and reserves, emergency control and learning.

## 2.4 Resilience Solutions in this Work

The focus of this thesis lies on the resilient enhanced grid operation, thus on the operational resilience. It leaves aside resilience enhancing methods for the infrastructure. In Table 2.1 the resilience solution provided by the developed grid operation are collected. Some of them, especially the first three, build the emphasis of this thesis, while the others are only minor aspects.

Table 2.1: Resilience solutions, their type of capability and where to find them in the thesis.

| Solution | Absorb | Adapt | Restore operation | Chapter |
|---|---|---|---|---|
| Distributed-hierarchical operation architecture | ✓ | ✓ | ✓ | Chapter 7 |
| Combination of optimisation and local control | ✓ | ✓ | | Chapter 9 |
| Automated self-healing | | ✓ | ✓ | Chapter 10 |
| Suitable communication infrastructure | ✓ | ✓ | | Section 11.2.1 |
| Bad-data detection in measurements | ✓ | | | Section 11.2.2 |
| Validation of control signals against local measurements | ✓ | | | Section 11.2.3 |

# CHAPTER 3

# Objective and Structure of this Thesis

The main objective of this thesis is the investigation and realisation of resilience enhancing architectures and functions for the operation of the distribution grid. Thus, this thesis focuses on two aspects. On the one hand the choice and design of the architecture of the grid operation; on the other hand the development and implementation of suitable methods required for the grid operation that exploit the advantages of the architecture. These two main aspects are reflected in the two main parts of this work: "Resilient Grid Operation Architecture" and "Methods for Resilient Grid Operation". The following summary lists the main scientific objectives and outcomes of this thesis.

**Scientific Outcome 1:** In this work, classifiers that allow the structural comparison and assessment of smart grid solutions are developed. This especially includes clear definitions of the types of operation architectures and aims to harmonise the inconsistency with regard to the use of terms like "distributed", "decentralised", "local" and "central" for the description of power system operation architectures. This scientific outcome is elaborated mainly in Chapter 5.

**Scientific Outcome 2:** This thesis analyses the resilience of different types of control architectures for the operation of the electrical distribution grid. It is shown that the combination of distributed and hierarchical control architectures for the realisation of grid operations is more resilient than centralised architectures. This is especially considered for threats that arise from the increasing dependency on ICT and is shown on a qualitative level by applying a resilience analysis cycle. This scientific outcome is elaborated mainly in Chapter 6.

**Scientific Outcome 3:** In this thesis, a distributed-hierarchical operation architecture is designed. It is shown that a distributed control architecture, in which the feeders of the medium voltage grid are operated independently, is a valid substitution of a central architecture. For many real world scenarios this distribution does not distort the operation. This also validates the fact that problems like voltage profile violations and congestions can be solved by interventions sufficiently close enough to the affected grid parts. To intercept situations where this approximation does not hold, the distributed control architecture is expanded by hierarchical layers. This scientific outcome is elaborated mainly in Chapter 7.

**Scientific Outcome 4:** In this work, a heuristic optimisation is formulated and implemented as standard way to optimise the grid operation and to solve all sorts of constraints that might occur in the distribution grid. This heuristic optimisation is benchmarked against a classic optimal power flow solver. This comparison shows that the heuristic optimisation leads to comparable results but provides more liberty in the definition of price functions. Further on, the aggregated multi-dimensional fitness function allows to flexibly define the weighting of the constraints and thus can find near-optimal solutions for cases where classic methods fail to solve the problem. This scientific outcome is elaborated mainly in Chapter 9.

**Scientific Outcome 5:** To provide the grid operation with self-healing capabilities, a distributed and automated self-healing method has been designed in this thesis. This method uses an evolving search space that finds new grid configurations within limited time, in near real time after a fault has occurred in the grid. Compared to other types of automated self-healing approaches it shows an increased resilience. This scientific outcome is elaborated mainly in Chapter 10.

The scientific outcomes 1 to 3 cover the investigations on the architecture and are therefore treated in the first part of this work. The second part of this thesis is dedicated to the new methods and functions and include the scientific outcomes 4 and 5. In more detail the structure of the thesis is as follows:

**Chapter 4** introduces the basic outline and structure of the electrical distribution grid. It further gives a literature review and state-of-the-art analysis of system architectures in related scientific domains like control theory, computer science and software development that influence the development of new power system operation methods. The review also mentions already industrialised approaches of new power system operation methods and economic concepts.

**Chapter 5** presents clear definitions of different types of grid operation architectures. This definitions leads to a set of classifiers that help to analyse the properties of power system operation methods.

**Chapter 6** analyses the behaviour of different operation architectures from the resilience point of view. This is done by applying a resilient analysis cycle and comparing local operation architecture, central architecture and the distributed-hierarchical architecture.

Taking all the previous chapters into account, **Chapter 7** validates analytically the idea of a distributed operation architecture for the distribution grid. To intercept situations where this distributed operation can lead to deficient results, the distributed architecture is completed by a hierarchical structure. It further on summarises the structure, actors, and roles of the distributed-hierarchical grid operation developed in this thesis as well as the interactions between the actors.

The focus of the second part of this thesis is on the methods for the grid operation.

In **Chapter 8** the main operation and control cycle is introduced that coordinates the behaviour of the grid operation. This coordination method is based on the so called power system traffic light, and assigns a phase - like the phases of a normal traffic light - to the grid state. This phase defines the actions taken by the grid operation.

**Chapter 9** gives details on two major control strategies applied for the operation of the grid: the heuristic optimisation as multi-purpose tool to optimise the grid state and the local control strategies as fall back strategies.

The self-healing capability is one of the major functions for a particular resilient grid operation. Thus, **Chapter 10** proposes and validates a self-healing method specialised for the distributed-hierarchical operation architecture.

As an addition to the previously explored architectural properties and functions, **Chapter 11** lists a set of further measures to increase the resilience of the grid operation even more, especially against cyber related threats.

This thesis ends in **Chapter 12** with an insight into the validation and testing activities that were used to increase the technology readiness level of the developed solutions of this thesis.

The conclusion and outlook is finally given in **Chapter 13**.

# PART II

# RESILIENT GRID OPERATION ARCHITECTURE

CHAPTER 4

# System Architectures

For long years, the distribution grid was a passive system, containing hardly any components that allowed monitoring and control. As described in the introduction, this is currently changing. The distribution grid is transforming into an automated system. The open question, that has been and is still investigated intensively in research, is how this automated system will be designed, and how the control architecture will look like. The answer to this question is strongly connected to the physical structure of the electrical distribution grid. Thus, this chapter starts in Section 4.1 with a short introduction into the set up and structure of the distribution system as it is presupposed throughout this work.

Meanwhile, the power system is not the only socio-technical system that needs an answer to the question of how to design its control and operation architecture. Further on, the development of new "smart grid solutions" is not only done by classic power engineering. Also neighbouring research disciplines like control theory and automation, information and telecommunication technology and computer science as well as electronics contribute to this active field of research. Therefore, Section 4.2 and Section 4.3 review design principles of system architectures in neighbouring research disciplines. And Section 4.4 gives a brief introduction into communication architectures. These architectures build the basis for the architectural classifiers proposed in Section 5.2.2 for the context of power system operation.

The work of this thesis does not only stand at the crossing between different research disciplines, it also stands at the transition between research and industrial application. Thus, the literature review given in this chapter does not only contain references to research but also presents in Section 4.5 recent industrial realisations of new grid operations and architectures.

Further on, this review chapter is not limited on technical architectures. In Section 4.6 a more economic and regulation related architecture concept is presented, the concept of flexibilities.

## 4.1 Structure of the Electrical Distribution Grid

The power system delivers electricity from generators to loads and sometimes transports it over hundreds of kilometres. In this power grid one distinguishes several grid levels generally defined by the voltage. In the following, a European system configuration is assumed. This includes a transmission grid that transports the electricity over long distances connecting several countries. It is operated at a high or extra high voltage (220 kV and 380 kV) level. Regionally the electricity is transmitted on the subtransmission level with 110 kV or seldom 60 kV. This is called the high voltage level (HV). The distribution grid finally distributes the electricity to the end-customers and consists of two voltage levels: the medium voltage (MV) level with mainly 10 kV or 20 kV and the low voltage (LV) level with 0.4 kV [39, p. 19-25]. According to some definitions, the subtransmission level is also belonging to the distribution grid. Fig. 4.1 visualises the key elements of the distribution grid. The transmission system is generally operated by a transmission system operator (TSO), and the distribution system by the distribution system operator (DSO). As it has been stated in the introduction, historically the distribution system did not contain any generators. Instead, they were concentrated in large scale plants

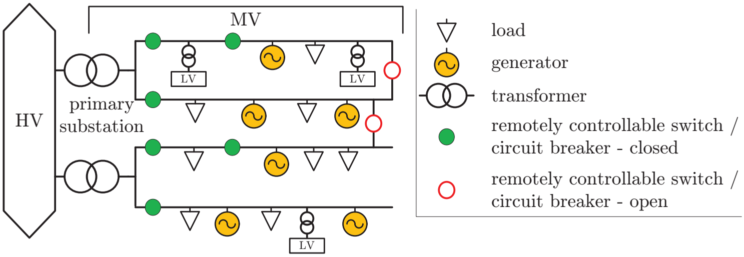



Figure 4.1: Structure and major elements of the MV distribution grid.

on the transmission level. This is nowadays changing, leading to distributed generators and controllable loads in the distribution grid.

The low voltage grid in rural areas is mostly built and operated in a radial way. This has the advantage that it is built at low cost and requires only plain protection, however it bears no redundancy in case of faults and damages. On the other hand, the high and extra high voltage grids are built and operated in a meshed way to guarantee n-1 security and a high service reliability. But this grid structure makes high demands on the protection scheme (e.g. distance protection). The medium voltage grid is often placed between these two concepts. It is mostly built in a looped or even meshed way, but operated in a radial form. Thus, it combines the advantages of a clear and simple operation and protection scheme with the advantage to be able to restore the supply or optimise the grid operation by the activation of switches.

Historically and until today, the transmission system belonging to one TSO is monitored and controlled by a central control centre uniting all the required competences to operate the system [40]. Also distribution grids are often controlled by control centres, with reduced functionalities and visibilities. But the authors of [40] see that this is going to change and that the future control centres will be distributed, integrated, flexible and open. The authors of [41] review different architectures and realisations of control architecture for the power system of the future. They highlight the needs for different forms of control in the power system depending on the control level.

The control centres are classically the heart of the grid operation. They are often equipped with supervisory control and data acquisition (SCADA). They include real-time monitoring and visualisation of power flows and the state of the grid. Classically all important decisions with regard to the operation of the grid are taken there. Often there is staff supervising the grid from the control centre 24/7. The responsible legal entity for the distribution grid and all the above introduced components is the DSO.

## 4.2 System Architectures in Control Theory and Software Development

Before choosing the architecture for the operation and automation of the distribution grid, it is worth considering the ideas developed by neighbouring research disciplines. Although new operation methods can often be described by mathematical models, the realisation and implementation of such methods requires a broader knowledge of ICT and computer science concepts. In this section, system architectures of control theory and software development are introduced. Section 4.3 gives an overview of design principles for architectures of artificial intelligence.

### 4.2.1 Control Theory

In control theory the classification of architectures of control systems is quite strict. They are even partly fixed by international standards prescribed by the International Electrotechnical Commission (IEC). This section aims to give an introduction into the basic control architectures.

#### Central Control

The "classic" way to organise control systems is to organise them in a **central** way. This means, they consist of one well-defined system that is controlled by one controller. This controller has the complete information about the system and sets all control variables related to the system [42, p. 1]. For the standard IEC 60050-351-55-09 a centralised control structure is a "control structure with interconnected sub-processes, in which each partial control equipment takes into account the information of all sub-processes to form its output information" [43]. Thus, it allows more complex internal structures of the system to be controlled.

#### Hierarchical Control

A common alternative to central control structures are **hierarchical** systems. Hierarchical control systems exist in two forms. In so called multilevel systems the controllers cooperate to achieve the same goal [42, p. 14]. For this, the higher level controllers coordinate the behaviour of the lower levels. On the other hand, in so called multilayer systems each controller has its own objective and the function that needs to be realised by the control system is divided [42, p. 14]. This is often done for systems that need control on different time scales, splitting the long-term and short-term control [44]. The standard IEC 60050-351-55-11 defines hierarchical control as a "control structure with several control levels placed one over the other, in which the control equipment assigned to a higher level coordinates the work of the control equipment assigned to the next lower level, providing for instance pre-determining control tasks, command variables, reference variables or final controlled variables" [43].

#### Decentralised Control

**Decentralised** control architectures rely on independent controllers each of them controlling a distinct subsystem. The input and output variables of these controllers are mutually different. Significant is that there is no information exchange between the controllers. Fig. 4.2 gives an example of a system controlled by two decentralised controllers. The IEC defines decentralised control structures in IEC 60050-351-55-10 as "control structure with interconnected sub-processes in which each partial control equipment takes into account only the information from its associated sub-process to form its output information" [43].

Because of the lack of coordination between the controllers, decentralised architectures can reduce the quality of the solution [42, p. 17]. This implies that decentralised control is only useful when the coupling between the subsystems and their input and output variables is weak [44].

#### Distributed Control

A **distributed** control architecture is basically a decentralised architecture but with information exchange between the controllers, see Fig. 4.3. The information that is exchanged between the controllers of the subsystems is either shared between all the controllers, so that all controllers receive (and send) the information of all other controllers. In [44] this is called fully connected. If the information between the controllers is only partially exchanged, so that some controllers only receive from and send to a subset of the other controllers, the architecture is called partially connected. Further on, one can distinguish between independent controllers, where the local controller has a local objective, and cooperating controllers, where the controllers optimises a global objective in a cooperative manner [44].

The distributed control architecture is less strict defined as the concepts above. Note 1 of IEC standard 60050-351-55-09 even says: "A centralised control structure can also be built up with distributed and interconnected control equipment which communicate with each other" [43].

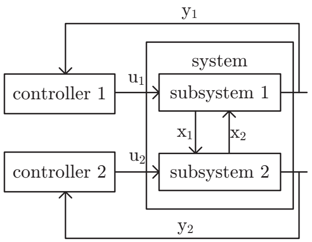



Figure 4.2: Decentralised control architecture composed of two subsystems with independent controllers; according to [44].

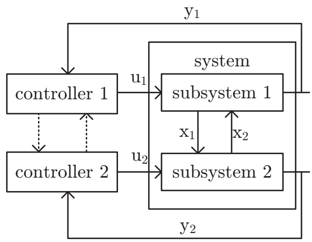



Figure 4.3: Distributed control architecture composed of two subsystems with information exchanging controllers; according to [44].

### 4.2.2 System and Software Architecture

In computer science, the branch of system or software architecture deals with the structure of software systems. An important aspect when organising the components of such systems is how strong subsystems are mutually depending on each other. According to the authors of [45] the analysis of a particular software problem mostly reveals that the overall task can be split up in different subtasks. If these subtasks can be organised so that they can work independently from each other, and require only very little data from other subtasks, they are called loosely coupled. Otherwise it is a tight coupling [45, p. 7-9]. Loosely coupled systems are candidate systems for the realisation of "distributed systems". In the context of system and software design the following definition holds for the term "distributed":

> "A distributed system is one in which components located at network computers communicate and coordinate their actions only by passing messages." [46, p. 17]

In the course of the increasing research and application of distributed IT systems, several concrete architectures that implement the distributed concept have emerged. The following non-exhaustive list gives an overview. It is derived from [45]. The architecture is chosen according to the level of looseness and independence one wants to realise.

**Client-server architecture:** This is the classic way for distributing tasks throughout a system. It realises clear roles between the provider of resources (server) and user of resources (client).

**Multi-tier architecture:** To handle the complexity the multi-tier architecture separates the overall system into several tiers layers of client-server architectures depending on the task.

**Service-oriented architecture:** Services are separated and loosely coupled via a message bus that acts as middleware. There is no strict separation between client and server. Loosely-coupled services are provided mutually between the components.

**Peer-to-peer architecture:** This architecture overcomes the classic client-server distinction. Every peer can communicate and use the resources of the other peers. As no central instance exists, this architecture needs to be self-organised.

## 4.3 Architectures for Artificial Intelligence

Also in research fields related to artificial intelligence, the question of how to place intelligence in a given environment with the greatest benefit is investigated. In [47, p. 6ff] a list of reasons and conditions is given where it can be advantageous to distributed intelligence:

1. For problems that are physically distributed.
2. For problems that are widely distributed and heterogenous in its functions.
3. For networks that force to take a distributed view.
4. For problems where the complexity dictates a local point of view.
5. For systems that must be able to adapt to changes in the structure or the environment.
6. As software engineering is moving towards designs using concepts of autonomous interacting units.

One can especially identify case 1, 2 and 4 that apply to the power system. The authors of [48] take this step and consider the best places and functions to make use of distributed artificial intelligence in the power system. The authors of [49] give a list of important features a grid operation of the future should support:

**Modularity:** New components and functions can be easily integrated into the system.

**Scalability:** Once installed, the system can be expanded to integrate more devices, or cover a larger area.

**Reconfigurability:** System can easily and without interruption change its structure.

**Robustness:** A robust system does not contain a single point of failure. It continues to work also if some components break down.

According to the above mentioned work, all these aspects can be realised best with a distributed multi-agent system (MAS). As the MAS is an important concept to realise distributed intelligence it is further detailed in Section 4.3.1. Also the grid operation developed in this work can be seen as a multi-agent system. Related to the concept of multi-agent systems but with a strong focus on the physical environment are cyber-physical systems. They are introduced in Section 4.3.2.

### 4.3.1 Multi-Agent System

The term **agent** as it is used in computer science and related fields is used highly imprecise. A very general and more or less generally accepted definition is the following:

> "An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives." [50, p. 15]

The environment in this case could be a physical - like the power system - or a digital one - like a software environment [51]. As the IEEE Power Engineering Society's Multi-Agent Systems Working Group describes in [51], this definition includes components (e.g. classic protection relays) and software (e.g. antivirus software). With this definition it is difficult to distinguish between really new concepts and just "relabeled" ideas. Therefore the label "agent" is often combined with an adjective, trying to specify what type of agent actually is used. One generally acknowledged definition is the one proposed by Wooldridge and Jennings for an "intelligent agent" [52] [1]. According to this definition an intelligent agent should have the properties:

**Autonomy:** should behave independently without direct intervention,

**Social ability:** should be able to interact and communicate with other agents,

**Reactivity:** should react to changes in their environment,

**Pro-activeness:** should not only react but also anticipate.

There exist several other properties that help to define agents. Franklin and Graesser give a list of possible properties like: learning, communicative, mobile, flexible, temporally continuous, goal-oriented [53]. The actors that are developed and applied in the here presented work can be seen as reactive, autonomous, temporally continuous, communicative agents.

Normally not only one agent but several are used that interact with each other. They then build a so called **multi-agent system**. In such a system the agents exchange information by using communication. The environment can be the same for all agents but the part of the environment each agent can control is generally at least partly different. This part of the environment is the "sphere of influence" of an agent [50, p. 105f].

Since its introduction, agents and multi-agent systems have been used in power system research for different purposes. One early work from the authors of [54] relies on a multi-agent system for the control of a microgrid. The authors of [51] and [55] review the major applications of multi-agent systems in power systems until the year 2007. They give also a list of benefits that result from the use of multi-agent systems in power systems. In [49] the authors review important projects that use the concept of agents until the year 2014.

A lot of the work reviewed in the papers above is very grid operator centric. Another way is chosen by the approach called "PowerMatcher". It puts the end-consumer and local markets into the centre and tries to balance demand and supply already down in the low voltage grid [56]. It automatically matches the energy sold by small scale generators with the demands. This match follows strictly market rules.

[1] This definition is called the weak notion of agency. There exists also a strong definition, specialised for the use in artificial intelligence that limits the scope of what an agent is even more. It contains attributes like knowledge, belief, intention [52].

### 4.3.2 Cyber-Physical System

Multi-Agent systems that interact strongly with a physical environment can be called **cyber-physical systems**. They are characterised by software embedded in physical components. But they go beyond classic embedded systems by relying on strong cooperation via network techniques between the components. They thus combine a whole bunch of already existing technologies [57]. The field of smart grid is seen as one of the key application fields of cyber-physical systems in the future [57], [58]. When investigating the effects of cyber attacks on infrastructures like the power system, the concept of cyber-physical systems is important.

## 4.4 Communication Architectures

From a protocol point of view, a detailed classification of communication is available through the Open Systems Interconnection model (OSI model) in ISO/IEC 7498-1 [59]. It splits up every (tele-)communication into seven layers ranging from the physical transmission medium to the layer that directly interacts with the application that uses the communication. Most of these layers can be realised in different ways and by different architectures, making it difficult to speak about “the” communication architecture.

On the application layer one distinguishes generally between client-server architecture and peer-to-peer architecture [60, p. 86f]. For the transport layer, the most commonly used protocol is TCP, while on the network layer, IP is employed predominantly [60, p. 5].

The actual transportation between communicating entities is described by the physical layer and the data link layer that consider the physical characteristics of the carrier medium and its topology. Generally one needs to distinguish between wired and wireless carrier mediums and the physical characteristics that influence the architecture.

A high level distinction between architectures for communication networks is given by Baran in [61]. He distinguishes between centralized, decentralized and distributed communication networks.

## 4.5 Industrial Solutions

The work of this thesis stands at the boundary between research and industrial application. Thus, a literature review should not only contain references to research but at least hint at recent industrial realisations in this field. The difficulty is that most of the following documents are rather advertising brochures than serious scientific publications. Thus, the following review must be evaluated with care.

Siemens already proposed in 2012 a concept for the self-organised automation of the distribution systems [62]. This concept relies on intelligent software agents and especially targets the integration of renewable energies and the correct unbundling between the actors in the energy sector. But this product never reached its commercial rollout. The actual product that is sold today is the “Decentralized Energy Management System” that centrally controls the decentralised distributed energy resources [63].

The competitor ABB proposes a layered structure that assigns different functions with different complexities on different layers. The lowest layer realises a local control concept and the top layer is designed as centralised control relying on a control centre [64].

Schneider Electric, the manufacturer specialised for the medium and low voltage grid, proposes two types of solutions. On the one hand, the classic central distribution management system is further developed into the “Advanced Distribution Management System” (ADMS) uniting several new functionalities [65]. On the other hand, a list of new functionalities like the improvement of quality of service and the managing of voltage profiles is proposed as part of new intelligent secondary substations [66].

In cooperation with the University of Wuppertal, the company SPIE SAG proposed a comprehensive system for the operation of medium and low voltage grids that is called "iNES". This system runs fully automated and decentralised in the secondary substations. Its functionalities range from the analysis of measurement and state estimation to Volt/Var and active power control for the distributed energy resources and grid components like the on-load tap changer [67].

An approach that can either run centrally in the control centre or decentralised as new intelligent electronic device in substations is proposed by the company BTC. This approach relies on a so called "grid agent" that regulates the grid. It can dynamically reduce the feed-in of distributed energy resources and helps to avoid conventional grid reinforcements [68].

In the above given examples the most common communication protocol is IEC 60870-5-104. The main data model for the communication is IEC 61850.

## 4.6 Flexibility Concept

The sections above presents new technical concepts for the architecture of the grid operation of the future. Another concept more belonging to economics and regulation is the concept of **flexibility**. The authors of [69] define flexibility in the context of power systems as "[...] the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system."

There exist mainly three applications where flexibilities can be deployed:

1. For the portfolio optimisation of players on the energy markets
2. By the TSO for the exact balancing and maintenance of the frequency stability
3. For the resolving of constraints in the transmission and distribution grid [69]

In the work of this thesis, the focus lies on the last aspect, as it plays a key role in the grid operation of the distribution grid. Thus, for the rest of this work the term flexibility always refers to this application. A taxonomy, of how different applications of flexibility can be classified, can be found in [D5].

It is no coincidence that the raising interest in flexibilities in the distribution grid comes at the same time as the decentralisation and digitalisation of the power system. Both aspects are trigger and enabler of flexibilities. Trigger, as the increasing decentralisation of generation requires flexibility. Flexibilities are used to mitigate costly grid reinforcement measures and allow the provision of ancillary services by distributed energy resources [70]. Enabler, as the selective and automatic activation of flexibilities is only possible with an appropriate ICT infrastructure.

When handling the flexibilities of lots of small scale units on different markets for different purposes a new role is required: the so called **aggregator**. As the authors of [70] describe it very generally, the aggregator is a service provider, that aggregates flexible generators and loads and that represents them at the energy or capacity markets. For renewable energy resources that can only be forecast with a level of uncertainty, the aggregator is responsible for the balance in case of forecast deviations. Thus, the shorter the time duration that needs to be forecast, the better for the aggregator. The aggregator also would be the interface vis-à-vis the DSO for the use of flexibilities to solve constraints in the grid. Important difference of this flexibility concept compared to e.g. operating reserves, is that they have a more or less strong coupling to a geographic location. Local constraints like voltage profile violations can only be solved with locally available flexibilities, although the required geographic accuracy depends on the circumstances and the contingency to be solved [71]. Sources of flexibility could be renewable energies like PV systems, wind generators and biogas plants. But they could also be realised as controllable loads. This is often referred to as demand side management. A very promising concept is to use electric vehicles for the flexibility provision [71]. Table 4.1 gives an overview over most prominent flexibility sources considered in the work of this thesis.

In addition to these market related flexibilities that are provided by generators or controllable loads, this thesis also uses the concept of grid flexibilities. These are flexibilities in the operation of the grid that arise from the grid itself and include the tap position of on-load tap changing transformers(OLTC) or capacitor banks. These types of flexibility also have a strong coupling to a geographic location.

Table 4.1: Flexibility sources considered in the work of this thesis.

| Device | Flexibility type | Scheduling |
|---|---|---|
| PV system | Reactive power, decrease of active power injection | Depends on meteorological conditions |
| Wind generator | Reactive power, decrease of active power injection | Depends on meteorological conditions |
| Biogas plant | Active and reactive power | Can follow schedule |
| Batteries, e.g. in electric vehicles | Active and reactive power | Can follow schedule |
| Controllable Loads | Generally active power | Limited on user preferences and needs |
| **Grid flexibilities** | | |
| Tap position of OLTC | Voltage ratio | |
| Switch position | Grid configuration | |
| Capacitor banks | Reactive power | |

For the author of this thesis, the natural restriction on locally available flexibility to solve local problems is one of the reasons to develop a distributed control architecture. This places the decision taking unit of the grid operation as close as possible to the source, as well as the solution of possible problems. The idea to use flexibilities can be combined with the traffic light concept introduced in Section 8.1 as it is presented in [70].

The questions on how one would design such regional market places for flexibility and how the flexibility prices are set are omitted in this thesis as they belong primarily to economical choices.

## 4.7 Conclusion

After introducing the key structure of the electrical distribution grid, this chapter reviews major system architectures from neighbouring research disciplines. This review shows, that the appropriate distribution of resources has been and still is an important question.

According to the opinion of the author of this thesis, the question is not, if the grid is automated or not. The question is rather which architecture is chosen for the automation, and which regulatory rules are established for the interactions between the components. In this thesis, the distributed architecture, inspired by multi-agent systems, and including the flexibility concept, is further investigated in the following chapters.

# CHAPTER 5

# Smart Grid Solution Classifiers

The development of new ways to operate the grid and to realise the "smart grid" has been and is a very active field of research. This is realised from a multitude of different researchers with backgrounds from power engineering, automation, control theory, computer science and information technology. Depending on the perspective of the researchers these smart grid solutions have to fulfil different tasks under different conditions. To distinguish them, the solutions are often labelled with terms like "decentralised", "distributed", "local", "central", "peer-to-peer", "agent-based", etc. These terms aim to help the classification of solutions, but unfortunately a great confusion must be stated with regard to the use of these terms.

By means of a literature review on solutions proposed for voltage and reactive power control in distribution grids, Section 5.1 motivates the necessity to introduce clear definitions and classifiers for the assessment of smart grid solutions. This is done in Section 5.2 which introduces a set of classifiers and clearly defines different types of architectures for the grid operation. This is a novelty and the **first scientific outcome** oft this thesis, from the list given in Chapter 3. The work of this chapter is the result of a close collaboration between the author of this thesis and Friederike Meier, Fraunhofer IEE.

## 5.1 Motivation

A typical research question for the smart grid on distribution level is the provision of ancillary services through distributed energy resources (DER). To distinguish the different methods developed for this application, they are often labelled with different terms. As the following examples visualise, these terms are often not used systematically.

The term "distributed" for example is used highly unsystematically in power system literature and is often used to describe completely different approaches. In [72]–[74] the term "distributed" is used to describe an operation of distributed generators that does not require any communication with other generators or other grid controllers but relies on information that is locally available to allow voltage control. In contrast, the authors of [75] and [76] name the same type of voltage control "local control". The authors of [77] define "distributed control" as a structure where a "controller needs to communicate only with neighbouring nodes" whereas for the authors of [78] this type of control (controller exchange information only with neighbours) is called "decentralised". This limitation of the communication to the neighbouring controllers does not exist in [79] and [80]. There, controllers can exchange information without restriction to the geographic proximity and still the authors call it "distributed control".

The use of the term "decentralised control" is also highly unspecific. In [77] and [72] it describes a control architecture with reduced communication capability between the controllers. And according to [80], a "decentralised control" requires no communication at all.

Also the term "central control" is not as unambiguous as it might seem. For articles [72], [77] that deal with one fraction of a distribution grid, a central controller is one that gets all the information about this grid fraction. It processes all the data and initiates all the actions. But for a distribution system operator (DSO), that normally operates more than just one primary substation, central means in general central for the whole grid area that is belonging to this

DSO. In this context, “central” is a synonym for “running in the control centre”. And a controller that is hosted in a primary substation instead of the control centre and controls independently the downstream grid is a great shift away from a central control. This is for example the case for the work presented in [81]. For the underlying low voltage grid this is a central control, but from a grid operator perspective this is a highly non-central solution.

A comparable inaccuracy with regard to the label exist with regard to the term “agent-based”. The authors of [82] already showed that the difference between an “agent” and a standard “controller” is not always visible.

All the above cited papers present very innovative research. But the confusion with regard to the “labels” shows that in the current discussion clear definitions of these labels are missing. A reason for this mixed use of terms is that the development of methods for new grid operation methods is not limited to one dedicated research domain. Quite the contrary is the case: Especially in the context of smart grids, methods to operate the power system often combine aspects of control theory and automation with information and telecommunication, electronics and classic power engineering.

In engineering, the classic way to compare two solutions is to model them analytically and to numerically simulate and compare their behaviour. But this approach bears the risk to reduce a complex system to an oversimplified mathematical description. This might lead to important losses of characteristics. In a mere performance based comparison solutions might be equal in their numeric model but require different infrastructures and conditions which would not be discovered.

According to the opinion of the author of this thesis, it is important to consider both approaches: the performance of the method as well as its internal structure. This is particularly important for complex investigations for example with regard to reliability [83], resilience [26] and detailed techno-economic analysis [84].

The following section defines a set of classifiers that allow the assessment of the internal structure of grid operation methods. As it is illustrated by the examples above, key aspect is the explicit definition of architectural classifiers.

## 5.2 Classifiers

As already mentioned above, solutions for smart grid applications, or more generally power system operation methods, are usually more comprehensive structures than controllers in control theory or software solutions. They combine functions on different geographic levels and time scales with different objectives and different communication requirements. Comparing methods for the operation of power systems can be a very complex task. As the introduction of this chapter shows, it is not possible to simply assess solutions according to the adjectives associated with them as they might have different meanings. The European Committee for Standardization (CEN) also realised this quite early and published 2012 the “Smart Grid Reference Architecture” (SGAM) [85]. It is a framework that allows the classification and description of a specific method or an use case for the smart grid. This framework distinguishes between five different layers: business layer, function layer, information layer, communication layer and component layer.

The three classifiers developed in this work are inspired by this preliminary work but take a more technical and operational centred view on the smart grid. The classifiers are: **Objective(s)** (Section 5.2.1), **Operation Architecture** (Section 5.2.2) and **Communication** (Section 5.2.3).

### 5.2.1 Objective(s)

The objective can be seen as the reason why a particular solution is developed. As the authors of [41] describe it, the smart grid needs different functions on different time scales and different geographical levels. This ranges from the objective to reduce the high-frequent harmonics injection by inverter coupled energy resources to objectives like the system wide reduction of power losses.

Often the purpose of a method is multi-objective. The trade-off between objectives that sometimes even contradict each other is important. Often power system operation methods deal with operational constraints, such as the maximal capacity of lines or the maximal power output of a DER unit. Constraints can also be caused by regulation, e.g. the discrimination freedom. This leads to research questions that only make sense in a particular regulatory framework. A list of possible (high-level) objectives of smart grid infrastructures can be found in [86].

The objective of an approach should be related to performance indicators that allow the quantification and assessment of the performance of a system. The level of achievement of an objective by a particular operation method should be made visible by the performance indicators. Examples are the system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI), the overall power losses or the minimal or maximal voltage in a system.

Further on, the objective is the interface regarding the business dimension. Depending on the business model, the objective of an operation method will change. In summary, the classifier **Objective(s)** describes the objective of a grid operation including constraints that need to be met. It can be quantified by performance indicators.

### 5.2.2 Operation Architecture

The criterion **Operation Architecture** is related to three subcriteria that deal with the design of the operation units of a distribution grid: the input data, the method, and the output or control variables. Derived from the definitions introduced in Section 4.2 the following five types of architectures for the operation of smart grids are proposed. They deliberately are called "operation architecture" instead of "control architecture". Operation architecture in this work refers not only to the mathematical or conceptual models of the "control architecture" but includes the communication capabilities as well. The operation architecture indirectly implies the input and control variables and the methods or approaches that can be used to realise a certain objective.

#### 1. Local Operation Architecture

The local operation architecture is the architecture that limits the control on one device or one facility that is part of a complex system. It only relies on input data that is available locally without external communication. The influence of the local architecture is thus geographically limited. The operation unit of the PV system and the operation unit of the transformer tap control in Fig. 5.1 are examples for such an operation architecture. Apart from the information coming from its own sensors it does not consider additional data. The major advantages of the local architecture are the potentially short reaction cycles and no need for external communication. Classic droop control concepts [84], e.g. for primary voltage control, are usually realised with a local architecture.

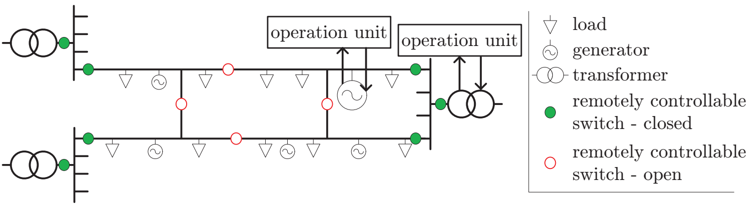



Figure 5.1: Local operation architecture for a PV system and a transformer.

## 2. Decentralised Operation Architecture

The decentralised operation architecture can be seen as an extension of the local architecture by increasing the assigned operation region from one facility to a subsystem of the total system. These subsystems are loosely coupled, like in the example of Fig. 5.2 the operation units in the different primary substations of one common grid area. Loosely coupled hereby means that the operation of one subsystem only weekly influences the other subsystems. This architecture requires communication to provide the decentralised operation units with the necessary input data from its subsystem and to transfer the set points of the control variables to the particular devices. As in Fig. 5.2, several decentralised operation units can exist in one system in parallel. In contrast to the distributed architecture described in the following paragraph, operation units in a decentralised architecture do not coordinate among each other.

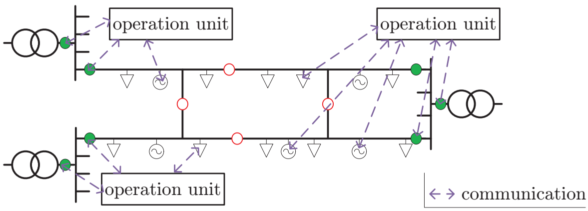



Figure 5.2: Decentralised operation architecture for the operation of a distribution grid. Each of the three decentralised operation units operates the grid area of a primary substation.

## 3. Distributed Operation Architecture

Like in the previous architecture, in the distributed architecture each operation unit is assigned to a certain part of the total system. Additionally, these operation units can exchange information among each other. As introduced in Section 4.2.1 one can distinguish between fully connected and partially connected architectures. In a fully connected architecture, every operation unit exchanges information with all the others. In a partially connected architecture, an operation unit can only exchange information with a subset of the other operation units. Some realisations of this architecture, that are especially popular in recent research, are based on operation units that only exchange information with neighbouring operation units like in [87]. This is often referred to as an agent-based architecture. This label is avoided in this work, as agent-based is rather a way to implement software than a control architecture. Fig. 5.3 shows a fully connected distributed architecture.

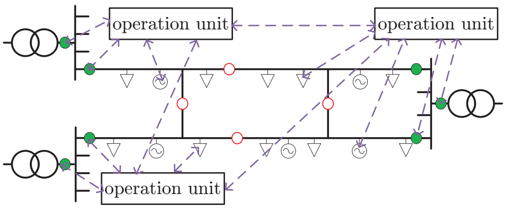



Figure 5.3: Distributed operation architecture for the operation of a distribution grid. The three distributed operation units can exchange information with each other.

### 4. Hierarchical Operation Architecture

In a distributed architecture the operation units are all equal, each responsible for its particular subsystem. In a hierarchical architecture the operation units are organised in several layers with a clear hierarchy and mutual dependency. Often the higher levels take over more coordinating tasks. A possible realisation is shown in Fig. 5.4. In this example, the operation units of the primary substations are coordinated from a higher level, for example from the control centre. Sometimes this type of architecture is also called "hybrid" [88].

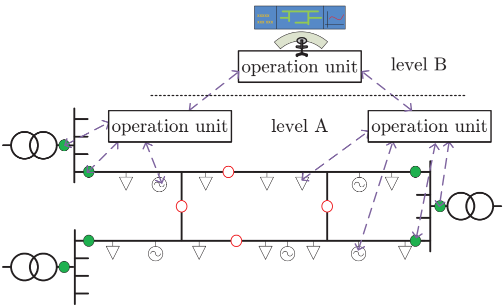



Figure 5.4: Hierarchical operation architecture for a distribution grid with two layers: level A and the supervisory level B.

### 5. Central Operation Architecture

In the central architecture there is only one operation unit for the whole grid area where all information of the system is gathered and processed and where all control decisions are taken, see Fig. 5.5. This is generally the case if the operation is part of the supervisory control and data acquisition (SCADA) system in the control centre. If the DSO has no control centre and only operates one primary substation, the central architecture would look like the decentralised architecture that only contains one grid. This definition also applies for microgrids [89].

### Real Operation Architectures

Practical realisations of grid operations will mostly be combinations of these architectures. Another aspect that is omitted in the above presented architectures is the degree of human

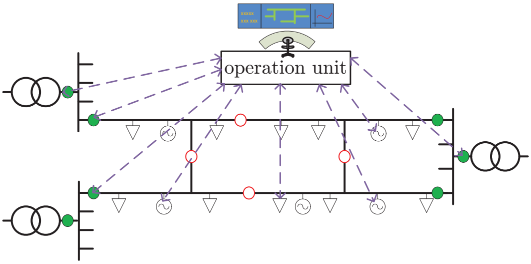



Figure 5.5: Central architecture of a distribution grid operation based in the control centre of the DSO.

involvement they require. Conceptually these architectures are all machine architectures. But in real world applications they would interact with humans and build a socio-technical system.

### Input and Control Variables

The above presented architectures indirectly imply the input and control variables. The following two lists give a non-exhaustive collection of possible input and control variables in the context of power systems. They define the physical parameters that are used as basis for the system models in the operation units.

**Input variables**

- Voltage (mostly magnitude; with phasor measurement also angle)
- Current (magnitude and direction)
- System frequency
- Active and reactive power flow over lines and transformers
- Load or generation at point of common coupling (active and reactive)
- Status information of protection devices, circuit breakers, fault passage indicators, switches, and tap positions
- Weather data

**Control variables**

- Active and reactive power set point of DER, controllable loads, and storage facilities
- Droop specification
- Tap position
- Operating point of capacitor banks
- Switch status

#### Method

The **method** describes the approach that is applied inside the operation unit(s) to realise the objective described in Section 5.2.1. The range of methods is large; it depends on the specific objective, the input and control variables and the required response time. There exist preferential combinations of methods and architectures. Local architectures are often realised as fast feedback control systems based on droop control. A classic approach to solve static problems in centralised architectures is to solve the optimal power-flow problem. For the solving of these non-convex power flow problems, a wide range of approaches have been developed [77], [90]–[92]. The authors of [77] give a review of appropriate methods suitable for voltage control for architectures of distributed or decentralised controllers. What sometimes leads to confusion is that a method itself can be distributed, as a form of software architecture like in [92], where the central control unit hosts a multi-agent system to solve the problem of optimal reactive power dispatch.

### 5.2.3 Communication

The capability to exchange information between components is a fundamental characteristic of smart power system operation methods. This communication capability is mostly conceived as a machine-to-machine communication, also called the internet of things. It adds to the already complex power system the communication system, building an interconnected network. But mathematical models of new smart grid functionalities often just specify the flow of information between the involved entities neglecting the technical realisation of the communication. According to the view of the author of this work, this is for several reasons a huge shortcoming. Communication is often limited in reliability, latency, bandwidth and security. The enhancement of these parameters is not possible without increasing investment and maintenance. Thus, communication is often the bottleneck of new power system operation methods. The aim of the classifier **Communication** is to make the requirements of communication clearly visible.

The classification that is proposed in this work for the communication in the power system context is more abstract and less detailed than the OSI model, introduced in Section 4.4. It consists of the three categories: **information flow**, **service layer** and **technological realisation**, see Fig. 5.6 for visualisation.

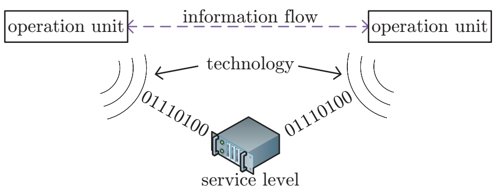



Figure 5.6: Categories to classify communication requirements of a smart grid solution.

#### Information Flow

The **Information Flow** describes which components exchange which information. It defines if the communication is a unidirectional or bidirectional communication. It also describes the timely requirements, how often information is exchanged and if this happens periodically or event based. The information flow can be interpreted as the input and control data according to Section 5.2.2 that needs to be communicated between the actors.

### Service Layer

If two partners exchange information, it depends on the communication method and the protocol that is used for the communication if this involves only the two partners or not. Prominent example is the e-mail, where the information flow as defined above goes directly from one user to another, but it involves at least one e-mail server. This is described by the **Service Layer**. Thus, the service layer describes the communication **topology**, e.g. if it is realised as client/server, peer-to-peer or middleware based communication. If the communication is **encrypted** the type of encryption is specified here as well. Also requirements with regard to the minimal **quality of service** can be given. Sometimes these questions can simply be answered by the choice of the **protocol**. The following list gives the main aspects that need to be answered to analyse this category. Sometimes not all aspects can be specified or they are already specified in another aspect

- Topology,
- Encryption,
- Quality of service,
- Protocol.

The service layer must be evaluated very carefully, especially for distributed control architectures as introduced in Section 5.2.2. In such systems the challenges associated with the usage of communication servers can lead to persisting problems. For example, the agent development platform JADE proposes messaging between its agents that allow a data flow between them. But the service layer of this communication is realised by a client/server architecture [93]. This destroys the distributed design principle that is generally core for all agent-based developments.

When using client-server architectures in microgrid applications, it is crucial that the server is hosted in the geographic area of the microgrid as well. Otherwise the communication within the microgrid is not independent and might not work correctly in islanded operation.

### Technology

The subcategory **Technology** finally covers the hardware and physical aspects of the communication. An important aspect of the category technology is the **transport medium**. This defines if the communication is wireless or wired, and in which particular realisation, e.g. if it uses coaxial cable or glass fibre, or which part of the elector magnetic wave spectrum. It further includes the type of technology and the physical topology of devices. The authors of [94] list the most prominent communication technologies suitable for smart grid solutions.

## 5.3 Conclusion

This chapter presents a comprehensive way to compare different smart grid solutions with each other. Focusing on the structural assessment, this chapter presents classifiers that cover all important technical aspects of a possible solution. This approach can be used to support business related decisions that need to take into account not only the quality of the possible solution but also the infrastructure and necessary requirements. It is also useful for other researchers to clearly categorise possible existing solutions and to highlight the degree of novelty of their own approach. Thus, it provides a tool for in-depth comparisons between power system operation modes. It further facilitates advanced investigations for example investigations with regard to the resilience of the solutions that depend on the interaction between all the different aspects.

# CHAPTER 6

# Resilience Analysis of Operation Architectures

The concept of resilience is introduced in Chapter 2 as design principle for technical systems, especially related to critical infrastructures. When it comes to the implementation of especially resilient systems, one of the challenges is to actually measure and determine it. How do you find out "the resilience" of a specific system realisation and compare it with "the resilience" of another realisation?

This limitation is reflected in the general lack of precise and quantifiable parameters in the definitions of resilience given in Section 2.2.1. Or as the authors of [29] put it: "Resilience is notoriously difficult to define much less to measure." These difficulties result not only from a lack of research on this subject but are conceptionally: One important aspect of resilience is to strengthen the system against unexpected, large scale new and underestimated disturbances [38]. So the authors of [38] conclude that it is very difficult or even impossible to conduct reliable cost-benefit analyses as part of resilience analysis. Other sources are not so pessimistic, but still raise the awareness of the fact that even quantitative assessment methods introduce a high degree of subjectivity into the assessment [26, p. 116]. Still, keeping these limitations in mind, resilience analysis methods can give further insight into the resilience of systems. And this is the objective of this chapter.

Possible types of architectures for distribution grid operations are defined in Section 5.2.2. In this chapter, they are analysed following a well defined process that aims to overcome some of the limitations stated above. This chapter starts with a short review of resilience assessment methodologies specialised for critical infrastructures and socio-technical systems. It then introduces in Section 6.2 the resilience analysis cycle that is applied in Section 6.3 to assess the resilience of different types of grid operation architectures against ICT related disturbances.

This chapter aims to demonstrate the positive qualities the combination of a distributed and hierarchical control architecture has on the resilience, especially with regard to ICT related threats. This resilience analysis according to the resilience analysis cycle is defined as **scientific outcome 2** in Chapter 3.

## 6.1 Review of Resilience Assessment Methods

The term resilience analysis or resilience assessment describes the process of deriving qualitative or quantitative ratings about the resilience of a system against a certain disturbance. A comprehensive review of resilience assessment methods in different scientific domains is given in [24]. Also Biringer, Vugrin and Warren review in [26, p. 84-101] major works for resilience assessment.

Generally the literature distinguishes between two concepts of resilience assessment approaches: the "structural assessment", or the "performance-based assessment" [26, p. 79]. In the structural assessment the inherent structure and the capabilities of a system are analysed to derive information about its resilience. This assessment is often a qualitative one. In the performance-based approach, the behaviour of the system is actually measured, and expressed by compressed figures. This is done without looking at the internal structure of the system but on the actual behaviour of the system (in real word scenarios) or of a model of the system (in simulations). As the performance is measured, this approach is generally quantitative. These two approaches can be combined for a more comprehensive view to form a “hybrid approach” [26, p. 79]. This is done in the assessment method called “Infrastructure Resilience Analysis Methodology” (IRAM) proposed by the Sandia National Laboratories and published in [26]. As the name implies, this method is especially designed for critical infrastructures like the power system.

A trend in recent years is to increase the interdependency between different critical infrastructures [31]. With regard to resilience this requires comprehensive assessment methods. Nan and Sansavini propose a quantitative method for this, that is especially applicable on the power system [31]. In its concept, this approach is not far away from the approach proposed in [26, p. 105-129]. As described in Section 2.3, in power systems the difference between operational and infrastructure resilience must be considered. To respect this also in the assessment, the authors of [34] propose metrics and assessment approaches for both types of resilience.

## 6.2 Resilience Analysis and Improvement Cycle

The resilience analysis of this work follows the resilience analysis cycle first published in [95, chap. 2] and further developed in [D15] with contributions of the author of this thesis. It follows the standards developed for the analysis of functional safety and risk management and proposes an analogues approach for the analysis of resilience in socio-technical systems [95, chap. 2]. The following section gives general information about this resilience analysis process. Its core, the resilience analysis cycle, is introduced in Section 6.2.2.

### 6.2.1 General Characteristics

The generic resilience analysis and improvement cycle that is applied in this work is intended to be a reference for the evaluation of resilience of socio-technical systems. The focus lies hereby on the technical aspects that lead to a certain resilience behaviour and not on management or organisational properties. The resilience analysis and improvement cycle tries to be a “tailorable, reproducible, certifiable processes” [95] for the increasing demand in meaningful and compatible evaluations of resilience.

In contrast to most of the above presented resilience assessment methods, the cycle is generic enough to not distinguish between quantitative or qualitative analysis. These are rather two parallel aspects and which way is chosen depends on the system, the level of detail and the intensity in which the system is investigated. This approach is close to classic functional safety processes, where different methods in evaluating the system are possible but lead to different so called safety integrity levels [96].

### 6.2.2 Resilience Analysis Cycle

The resilience analysis and improvement cycle defines the core of the iterative process for the analysis and improvement of the resilience of a system. Fig. 6.1 gives the general outline and an overview over the 9 steps of this analysis cycle.

In the steps (1) to (4) the system(s) under investigation are analysed to derive the key system performance functions and possible threats or hazards that could lead to disruptions.

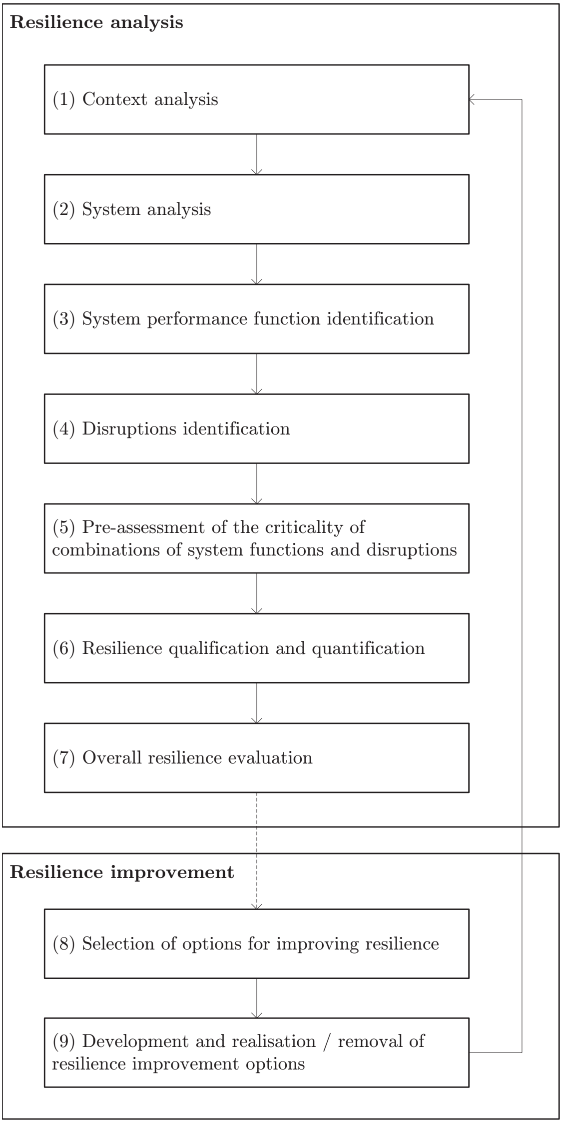



Figure 6.1: Resilience analysis and improvement cycle; advancement of process described in [D15].

These steps provide the input and boundary conditions for the main analysis in the steps (5) to (7). Especially important is thereby step (5) where the system functions derived in step (3) and possible disruptions derived in step (4) are brought together to identify critical combinations. If quantitative methods are used in (6), this step leads to comparable measure values. If qualitative methods are used, step (6) results in a textual description. Both outputs are then evaluated in step (7), by considering not only particular system functions, but the overall system(s). Thus, step (7) is more a management than an engineering step.

Step (8) and (9) give the generic outline of the approach to increase the resilience of the system(s). After increasing the resilience of a system the analysis cycle must be re-evaluated to actually assert the increase of the resilience and to validate the resilience increasing measures.

## 6.3 Resilience Analysis of Grid Operation Architectures

Based on the resilience analysis cycle introduced in the previous section, a resilience analysis is performed to compare the resilience of different types of grid operation architectures against disturbances originating from the interconnected ICT system. Thus, this analysis omits the steps (8) and (9). The analysis investigates the systems on a conceptional level, and thus tries to avoid the analysis of particular implementations. But this implies that some aspects stay rather vague, and solely a qualitative analysis is possible. This analysis further assumes that the systems are constructed according to the best practice and state-of-the art principles but without any unusual and additional security mechanisms.

In the following the steps described in Section 6.2.2 are processed.

### 6.3.1 (1) Context Analysis

The systems that are investigated in this analysis are three types of operation architectures for the distribution grid. Thus, the systems include the control architecture, the communication capabilities (if necessary) and the power system infrastructure. Such an interdependent system is generally called a “smart grid”. The objective of this analysis is to identify the resilience capabilities of the operation architectures against ICT related disturbances.

The key stakeholder of these systems is the distribution system operator (DSO), although the clients connected to the grid are also strongly affected by consequences that disturb the correct functioning of the distribution grid. Therefore the key functional objectives of the “smart grid” are to provide the clients with electricity, to transfer the electricity injected by distributed generators, to operate efficiently and to not put human beings into danger.

This analysis focus on ICT related disturbances. It does not regard disturbances from other sources like weather or other environmental influences. Further on, it only considers technical aspects and omits the influence of the behaviour and decisions of human beings and organisations on the resilience.

### 6.3.2 (2) System Analysis

The systems under investigation are the interdependent systems of the hardware dominated electrical distribution grid with its lines, cables, transformers, loads and generators and the software dominated control and operation system. This latter includes possible communication methods as well.

The distribution grid is structured according to the introduction given in Section 4.1. Thus it is a distribution grid that includes distributed generators and controllable loads. The control and operation system is basically an ICT system. The distribution grid and the operation system build together a cyber-physical system as introduced in Section 4.3.2. For the operation system three different architectures are assumed. They are detailed in the following paragraphs.

The design of the communication infrastructure required for the second and third control system follow the respective operation architecture. The operation architectures as they are assumed in this analysis are artificial architectures that in reality mostly will be realised in mixed forms.

### Local Operation Architecture

In the local operation architecture, the influence of the operation unit is limited on one particular device in the system, like in Fig. 5.1 on a PV system or on a transformer. Thus, in this operation architecture no communication is necessary, measurements and status information are only available from sensors directly integrated into the particular device. Operation units thus have a very limited view on the system, and can only react to locally available indicators. Generally they follow simple control loops. Also because of these simple control loops, operation units can generally react very quickly. Table 6.1 summarises major characteristics of this architecture. Although the operation is local, distributed generators are nowadays often equipped with a communication interface for installation and maintenance. This is mostly realised as some form of web service and thus is a form of central operation architecture.

Table 6.1: Characteristics of local operation architecture.

| | |
|---|---|
| Area of influence | Device |
| Reaction time | Milliseconds or faster |
| Redundancy | Generally not available |
| **Communication** | Not available / not required for operation |

### Central Operation Architecture

In a central operation architecture all information is gathered and processed in one operation unit. Classically such a system is called the supervisory control and data acquisition (SCADA) system, see Fig. 5.5. Also all decisions concerning the system are taken there, either automatically or by human beings. If the decision requires human intervention, response times below one minute are generally not possible. In the past, the communication between the control centre and the devices in the grid has been realised with utility owned communication networks that operate independently from the public internet. With the requirement to interface more and more distributed generators and controllable loads, the use of public internet is commonly accepted. To have some redundancy in case of major outages, the only possibility is to double the whole system and host this copy control centre at another place. The major characteristics of this operation architecture are repeated in Table 6.2.

### Distributed-Hierarchical Operation Architecture

The last type of operation architecture is a combination of a distributed and a hierarchical operation architecture. In the distributed architecture, each operation unit operates a part of the overall system, e.g. one feeder. The superordinated operation units in the hierarchical order supervise all the operation units belonging to its portion of the overall system. It can intervene if necessary or take over the operation in the case of disturbances or inadmissible operation. This already includes some redundancy into the architecture. The communication in such an operation architecture should reflect the operation architecture and be as distributed

Table 6.2: Characteristics of central operation architecture.

| | |
|---|---|
| Area of influence | Grid area of one DSO |
| Reaction time | Seconds (automatically) or minutes (human intervention) |
| Redundancy | Double complete system |
| **Communication** | Required |
| Topology | Centralised |
| Protocols | e.g. IEC 60870, IEC 61850, public internet |
| Technology | Ethernet, wireless and mobile network |

as possible and be independent from external resources outside of the area controlled by the architecture. Otherwise concepts like the operation of microgrids in islanded mode can be problematic, as the communication might no longer be possible. A candidate technology for such a communication is power line communication (PLC) or radio transmission. Table 6.3 summarises major characteristics of this operation architecture.

Table 6.3: Characteristics of distributed-hierarchical operation architecture.

| | |
|---|---|
| Area of influence | Feeder or primary substation |
| Reaction time | Milliseconds to seconds |
| Redundancy | By other actors |
| **Communication** | Required |
| Topology | As distributed as possible, peer-to-peer |
| Technology | Power line, radio transmission |

### 6.3.3 (3) System Performance Function Identification

As it has already been stated in the context analysis, the key function of the power system is the provision of electricity for the clients requiring it. The authors of [86] break this key function down into a list of targets the power system of the future must comply with. The major targets that should be realised with a grid operation are:

- Keep the loading of lines, cables and transformers always below the rated capacity.
- Keep the voltage within its tolerated bandwidth.
- Reduce the power losses.
- Provide the best possible supply reliability.
- Equip the grid with islanding capabilities.

The last target differs from the other targets, as it is more an operation mode than an operation objective. These targets are related to performance indicators. They measure the degree of fulfilment of targets. To meet the targets, main system functions are available. They build the key functions of the grid operation. The main system functions that result from the above given targets are:

- Shedding of load or generator,
- Voltage control,
- Reconfiguration / self-healing,
- Islanding droop control, grid forming.

The effectiveness of these system functions is evaluated by the performance indicators. Appendix B summarises in the first three columns of Table B.1 the targets, performance indicators and system functions considered in this resilience analysis.

In this assessment the resilience of three different operation architectures is analysed. This means the influence of disturbances (that are identified in the next step) is investigated on the system performance functions. But not all functions are possible with all operation architectures. For example the local control architecture is not able to reconfigure the grid, while the central operation architecture in a control centre is not suitable for islanded microgrid operation. Further details can be found in Table B.1. This table investigates the application of the particular performance function in the particular operation architecture. The service functions that are considered in step (5) are marked with a blue background colour.

### 6.3.4 (4) Disruption Identification

The resilience analysis of this work focuses on disruptions that arise through the increased interconnection between the power system and the ICT infrastructure. Thus, it covers disruptions that have their origin in the ICT infrastructure and that through the interconnection of the two systems might have an influence on the performance of the power system. To identify possible threats on the ICT system the popular STRIDE model is used [97]. This model, developed by Microsoft, allows on a high level the classification of different types of security threats on ICT systems. The acronym STRIDE already gives the six major threat categories [97]:

**Spoofing:** In a spoofing attack, the attackers disguise themselves as something or someone else. Spoofing comes in two ways either by spoofing a real person and by taking over its account or by spoofing a machine. This allows the access to systems and data that is normally not accessible.

**Tampering:** During a tampering attack data is modified. This includes the modification of memory, code or files on a machine but can also mean the modification of data flows in a communication network.

**Repudiation:** To avoid the detection, attackers generally try to make their presence in a system invisible and non-detectable.

**Information disclosure:** The objective of an information disclosure attack is to obtain data or information for which the attacker (or the customer of the attacker) has no right to possess.

**Denial of service:** Denial of service attacks try to interrupt the correct functioning. This is done by absorbing the available resources of either communication networks or a machine by flooding it with data.

**Elevation of privileges:** The elevation of privileges attacks overcome the general security mechanisms of giving processes only limited privileges.

A direct disturbance of service functions results mainly through tampering and denial of service attacks. All the other threats are side effects or preliminary attacks that do not directly interfere with the service function execution. Thus from a criticality perspective especially these two threats (with both the attack on the machine and the attack on the communication network) need to be considered. From an effect perspective, these attacks can be used to disturb the operation of the grid. In advanced forms, if safety margins are no longer respected, they can also destroy grid components and endanger human beings.

### 6.3.5 (5) Pre-Assessment of the Criticality of Combinations of System Functions and Disruptions

Depending on the operation architecture, the disruptions can have different effects on the system functions and the overall system. In general, tampering requires more detailed knowledge about the system that is attacked than denial of service attacks. Thus the effort might be larger.

#### Local Operation Architecture

For the local operation architecture, all disruptions that originate from the communication system can be neglected, as no communication is available. As the area of influence is rather limited for local operations, the impact of disturbances is also geographically limited.

Table B.2 provides the full pre-assessment for the local operation architecture.

#### Central Operation Architecture

Compared to the other two operation architectures, central operation architectures like control centres are generally good protected, physically but also digitally. A vulnerability that is increasingly putting the system at danger, is the connection of the control centre to the public internet. Historically, control centres were only using proprietary and independent communication paths. As the control centre operates a geographic extensive area, especially tampering and abusing the system functions can have devastating effects.

Table B.3 gives more details about the efforts and impacts of disturbances of the system functions in the central operation architecture.

#### Distributed-Hierarchical Operation Architecture

The impact of disturbances targeting the communication network depends on how the communication is realised between the actors of the distributed-hierarchical operation. Generally the physical protection is more difficult as the devices are widespread but also the affected area is limited.

Table B.4 summarises the detailed efforts and impacts of all types of disturbances.

### 6.3.6 (6) Resilience Qualification and Quantification

Based on the pre-assessment in the previous step, this step evaluates the resilience of each of the critical combinations of disturbance and system function. This can be done qualitatively and / or quantitatively, depending on the system and the desired outcome of the resilience analysis. As described above this resilience analysis does not consider quantification but tries to be as general as possible. Thus, only a resilience qualification is performed. The major input for this step are the system functions identified in (3) and the disruptions identified in (4).

The analysis of this step is given in the tables Table B.2 to Table B.4. In the following the main outcomes are summarised.

#### Local Operation Architecture

The huge advantage of the local operation architecture with regard to its resilience is that it does not require any remote communication for the operation. This makes it tiresome for large scale disturbances, as every device has to be accessed manually. Thus, it is difficult to realise large-scale cascading disturbances. Nevertheless, an outage or attack against a device is disagreeable for the affected proprietary as this could lead to destroyed devices.

#### Central Operation Architecture

As has already been mentioned in the previous step, especially critical for the central operation architecture is the connection of the control centre to the public internet (even if secured by firewall etc.). This gives possible attackers the chance to attack from everywhere in the world. And once the access is gained on the private network, issuing false switching signals can cause tremendous disturbances. This is not only affecting the directly switched areas, but can - if the areas are large enough - lead to problems everywhere in the interconnected system, as the frequency balance might be disturbed. Especially dangerous in such a case might be the combination of a tampering and a denial of service disturbance, because this allows the attackers to do whatever they want and at the same time deprives the control centre from intervention.

#### Distributed-Hierarchical Operation Architecture

The major problem that comes with the distributed approach is that it is much more difficult to physically protect the devices that are communicating with each other. So the risk of someone entering the system is much higher. But here the design of the communication network is important. To maximally benefit from the distributed control, the communication should also be rather regional, without the necessity to rely on resources outside the particular geographic area. This again reduces the risk of illegal access, as physical presence is required to penetrate into the system.

### 6.3.7 (7) Overall Resilience Evaluation

This last step includes the outcome of the previous steps of this analysis cycle in the overall system context.

#### Local Operation Architecture

From a pure resilience perspective, the local operation architecture is the most resilient one. However, because of its limited local view, it can not provide all the important functions required for a complete grid operation. Yet, the possibility to react quickly and without any communication on critical situations in the grid make it an ideal candidate for emergency fall back strategies. This is why the grid operation of this work also includes some local control elements, see Section 7.5.3.

### Central Operation Architecture

The analysis of the previous steps validates the criticality of the major worry that DSO have when it comes to the dangers of ICT related emergencies: That someone hacks into their systems, takes over the control and leaves the clients in the dark. Especially the connection to the public internet makes this a potential scenario.

Further on, central control centres introduce a single point of failure into the system. Practically, this single point of failure is mostly eliminated by providing a double control centre somewhere in the grid area, from where the operation of the grid can be resumed. But this full redundancy is quite cost intensive.

### Distributed-Hierarchical Operation Architecture

The distributed-hierarchical architecture already provides some kind of redundancy, as neighbouring or superior actors can step in if an operation unit breaks down. And even if this is not possible, the effect is rather limited. To increase the effectiveness of distributed control, heterogeneity with regard to its soft- and hardware is important. This makes the distributed system for example immune against self-propagating worms but can increase costs and efforts especially for maintenance. This thesis relies on the inherent positive properties of this type of control architecture and extends it with suitable methods and resilience enhancing capabilities. To allow an adequate grid operation, modified methods are required, that differ in the way, how classic central control would solve the problem.

### General Remarks

This analysis omits problems that might be caused by the need to update the software required for the operation. This is a problem that is generally not fully addressed, for any of the above given operation architectures. Until today, classic central control solutions are not, or very rarely, updated as often the whole system would no longer be operational. And updating distributed systems could be very tiresome, but could be done successively and thus avoiding a full shut-down.

## 6.4 Conclusion

On a high level, this analysis evaluates general grid operation architectures with regard to their resilience against ICT related threats. To the knowledge of the author of this thesis, comparable investigations have not yet been conducted. Although the architectures might not be realisable one-to-one in real world implementations, such analyses help to uncover hidden flaws and can be used to benchmark realisations. As a result of this analysis, the distributed-hierarchical operation architecture is used as a basis for the implementation of the grid operation.

# CHAPTER 7

# Distributed-Hierarchical Grid Operation

The previous chapter indicated that a distributed-hierarchical operation architecture is an especially resilient architecture for the realisation of a grid operation for the distribution grid. From an electrical behaviour point of view, Section 7.1 validates the assumption that the operation of the grid can be distributed and split up into the operation of independent feeders. Based on this assumption, Section 7.2 introduces the architecture and the basic components of the grid operation. This grid operation architecture is further detailed in Section 7.3 and Section 7.4. Further on, Section 7.4 gives a brief overview over the functions that are realised for each of the actors. They are further detailed in the next part of this thesis.

Depending on the operation conditions in the grid and the status of the actors, different interactions and coordination methods are available. They are introduced in Section 7.5.

All these points are aspects of **scientific outcome 3** as introduced in Chapter 3.

## 7.1 Validation of Distributed Control Architecture

A key assumption that builds the basis for the work of this thesis is that the electrical distribution grid does not have to be operated as one system. Instead it can be reasonably split up into subsystems that can be operated more or less independently and thus allows a distributed control architecture, as introduced in Section 5.2.2. This section validates this assumption from an electrical behaviour point of view by analytical investigations of a minimal system.

The general structure of the distribution grid introduced in Section 4.1 defines the outlines for possible control architectures. When investigating the behaviour of medium voltage grids, the reference bus of the system (also called slack bus) is often placed on the high voltage side of the primary substation of the medium voltage grid.

The left drawing on Fig. 7.1 gives the reduced scheme of a medium voltage grid with two feeders connected to a high voltage source. The two branches of this system represent two

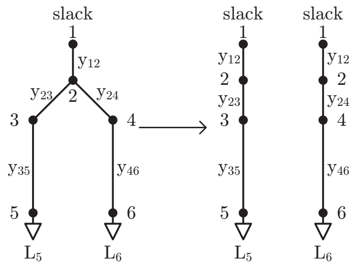



Figure 7.1: Two feeders of primary substation with shared transformer and bus bar.

feeders, and the shared connection between node 1 and node 2 represents the transformer and bus bar. The admittance $y_{nm} = \frac{1}{z_{nm}}$, the inverse of the line impedance, thereby describes the electrical behaviour of the connection between the nodes. This generally is a complex parameter, leading to complex values for the voltages as well as for the currents. The larger the admittance, the smaller is the impedance and the smaller are the electrical losses along the line. For each node of this system the Kirchhoff's law is applied and the sum of all currents is built:

$$\begin{aligned}
&\text{node 1:} && V_1 \cdot y_{12} - V_2 \cdot y_{12} = -I_{\text{slack}} && (7.1)\\
&\text{node 2:} && V_2 \cdot (y_{12} + y_{23} + y_{24}) - V_1 \cdot y_{12} - V_3 \cdot y_{23} - V_4 \cdot y_{24} = 0 && (7.2)\\
&\text{node 3:} && V_3 \cdot (y_{23} + y_{35}) - V_2 \cdot y_{23} - V_5 \cdot y_{35} = 0 && (7.3)\\
&\text{node 4:} && V_4 \cdot (y_{24} + y_{46}) - V_2 \cdot y_{24} - V_6 \cdot y_{46} = 0 && (7.4)\\
&\text{node 5:} && V_5 \cdot y_{35} - V_3 \cdot y_{35} = -I_{\text{L}_5} && (7.5)\\
&\text{node 6:} && V_6 \cdot y_{46} - V_4 \cdot y_{46} = -I_{\text{L}_6}. && (7.6)
\end{aligned}$$

The solving of Eq. (7.2) for $V_2$ leads to

$$V_2 = \frac{V_1 \cdot y_{12}}{y_{12} + y_{23} + y_{24}} + \frac{V_3 \cdot y_{23}}{y_{12} + y_{23} + y_{24}} + \frac{V_4 \cdot y_{24}}{y_{12} + y_{23} + y_{24}}. \tag{7.7}$$

To investigate the mutual influences between the two feeders, we are interested in the changes of $V_2$ that are caused by changes in $V_3$ and $V_4$, which for their part depend on changes in the loads $\text{L}_5$ and $\text{L}_6$. The voltage at node 1 $V_1$ is assumed to be constant and invariant (as it is the definition of the slack bus), and thus Eq. (7.7) can be transferred to

$$\Delta V_2 = \frac{\Delta V_3 \cdot y_{23}}{y_{12} + y_{23} + y_{24}} + \frac{\Delta V_4 \cdot y_{24}}{y_{12} + y_{23} + y_{24}}. \tag{7.8}$$

Now it is assumed that the impedance between node 2 and the slack tends to zero $z_{12} \to 0$. It follows that $y_{12} = \frac{1}{z_{12}} \to \infty$. Then the mutual influence of the two branches diminishes as the two terms of Eq. (7.8) tend to zero. Yet, if $z_{12}$ is "large" the two branches tend to influence themselves.

This asymptotic analysis can be concretised with figures from typical medium voltage lines and transformers. According to [98], standard type medium voltage transformers have admittance values $y_{\text{T}}$ between 240 SI and 600 SI. Standard types lines and cables have admittance values per km $y_{\text{L}}$ of 1.5 $\frac{\text{SI}}{\text{km}}$ to 6 $\frac{\text{SI}}{\text{km}}$ [98]. Thus, the quotients $\frac{y_{\text{L}}}{2 \cdot y_{\text{L}} + y_{\text{T}}}$ will be around 0.02 and 0.002 or even smaller for longer lines. Then, the transfer of changes in the voltages on one feeder on the voltages on the other feeder is in the range of percent or per mil.

This behaviour not only allows the distribution of control but enforces that problems like voltage profile violations or congestions in particular parts of the grid can only be solved by interventions sufficiently close enough to the affected parts. Thus, the distribution is not only possible, but sometimes there is not even the necessity to enlarge the problem.

At this point, one restriction must be given. The above derived results only hold for the assumption that the voltage magnitude of the high voltage grid is really unaffected by the changes in the downstream medium voltage grid, and that the localisation of the slack node is correct.

Appendix C validates the above described behaviour for an example grid. It also contains a test case that shows the limits of the distributed approach, as feeders under certain circumstances can negatively influence each other, especially if contradicting problems must be solved on neighbouring feeders. This finding justifies the major extension of the distributed operation by integrating it into an hierarchical structure. In the case of influences between feeders, the superordinated operation unit, e.g. supervising the primary substation and all feeders connected to it, can detect such influences between feeders and can intervene.

## 7.2 General Outline of Architecture

In Section 2.1 and Section 5.1 solutions and architectures for new ways to operate the distribution grid are reviewed. Most of the solutions presented there are concepts or contain simulation based proofs of concept. The majority originates from an academic background with only limited feedback from utilities and system operators. Section 4.5 on the other hand proposes industrial solutions that can be purchased more or less off-the shelf.

Although the here proposed architecture might share aspects of other solutions it is unique in its completeness. It does not only provide one application (e.g. optimisation of voltage bandwidth) but can be used as multi-purpose solution for a fully automated distribution grid. The operation architecture developed in this work tries to find an optimal balance between classic ways to operate the grid and new concepts. According to the knowledge of the author of this thesis, the dynamic interactions depending on the grid state that are described in Section 7.5 are a unique feature.

The basis for the architecture of the grid operation of this thesis has been developed as collaborative work as part of the European project DREAM[1] [D13]. A large contribution came especially from Emmanuelle Vanet who published aspects of this work in her doctoral thesis [99].

Preliminary to the work of this thesis is the work presented by the authors of [100]. The agent-based system introduced there also separates the market driven behaviour from the grid operation. Its "grid agent" can be seen as an ancestor of the here presented *DSO agent*.

The basic concept for the grid operation of this work relies on the assumption that constraints that result from the feed in of distributed generators or the increased charging of electric vehicles affect rather spatially limited areas. As has been shown in the section above, these constraints can only be solved by flexibilities and resources that are available in the vicinity of these elements. In other words, the design principle can be summarised by the slogan: "Solve local problems locally with locally available resources".

According to the architectures introduced in Section 5.2.2 the architecture chosen in this work combines elements of a distributed with a hierarchical architecture. It further on includes aspects of local control. According to the smart grid architecture model (SGAM) it could be placed between a fully centralised and a fully decentralised system [85, p. 19ff].

The grid operation that is developed in this work aims at the distribution grid and there mainly at the medium voltage level. Conceptually it also could be used on the low voltage level. But the level of automation and complexity is often higher on the medium than on the low voltage. The former has better preconditions and a higher need for a grid operation like the one developed in this work. Further on, this grid operation focuses on the real-time operation and omits forecast based behaviour. Real-time in this contest does not mean the strict compliance to so called "real-time constraints". It rather describes the reaction directly following the perception of some event. As some measurements in the distribution grid might be only available every minute, real-time could mean a reaction to these slow measurements. This weak and slow definition of "real-time" implies that only static effects are considered. Dynamic phenomena are omitted.

One could have considered a fare more distributed architecture, and could have relied much more on the cooperation between the different types of actors. While this is a popular approach in research [77], for real world applications this is a difficult idea. For the DSOs it is important to know that the grid operation lies actually in the hands of their own devices over which they have full control. This is also important with regard to legal questions.

[1]Funded by the European Commission under FP7 grant agreement 609359.

With all this considerations in mind, Fig. 7.2 shows all important components, elements and actors that are actively part of the grid operation presented in this work.

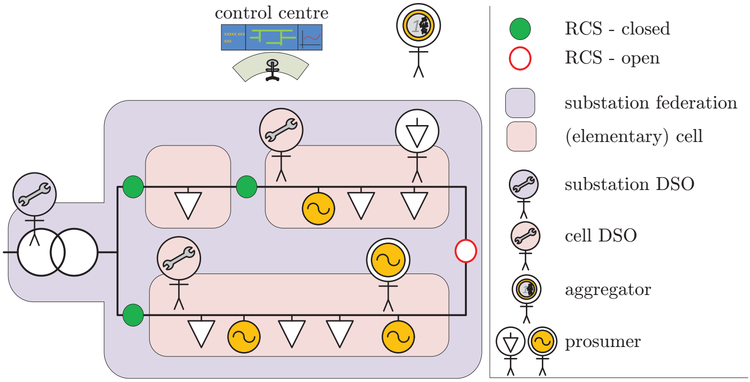



Figure 7.2: Architecture and components of the proposed grid operation.

The targeted grid for the use of this grid operation is a classic European medium voltage grid with a nominal voltage of 10 kV to 30 kV. The connection between the medium voltage grid and the upstream high voltage grid is realised by a primary substation. This primary substation contains the transformer(s) and distributes the power flow on the feeders. It contains additional devices like measurement infrastructure, protection devices and circuit breakers. These devices are generally called intelligent electronic devices (IED). This grid operation is especially designed for the use with radially operated medium voltage grids. This is a very common structure, especially for rural areas. The radial structure has huge advantages with regard to the protection but bears no redundancy in case of faults and damages. This drawback can be overcome by constructing the grid in loops or even meshes (as in Fig. 7.2). In case of a fault, the grid configuration can be changed and loads can be resupplied. These loads connected to the medium voltage grid can be "real" medium voltage clients like companies and facilities or downstream low voltage grids. Generators in the medium voltage grid are mostly renewable energy resources and can be larger PV systems (with an installed power larger 100 kVA), medium sized wind generators and biogas plants. Physically they are often not-rotating generators but inverter-coupled devices; this is especially true for PV systems.

Regularly switches are installed in the grid. They allow the isolation of components in case of failure and maintenance or the changing of grid configuration. In the following, the term grid topology always refers to the way in which the grid is built. Grid configuration means the way the grid is operated, e.g. which switches are open and which are closed. Most of these switches are manual switches that require the on-site activation. In intersections and other important places in the grid, these manual switches are often replaced by remotely controllable switches (RCS). These switches can be activated by remote signals generally issued from the control centre. Remotely controllable switches are often combined with Remote Terminal Units (RTUs) that provide the interface between the switch and the necessary communication capabilities. In France, a feeder contains on average 2 RCS [101]. Often circuit breakers at the feeder in the primary substation also can be remotely controllable.

In this grid structure, visualised in Fig. 7.2, the new grid operation architecture is introduced. The following sections describe the key structural elements and the main actors and roles.

## 7.3 Structural Elements

An important concept of the here presented grid operation is the division of the grid into several areas. The idea to subdivide the grid in smaller dedicated entities is not new and not exclusive for this approach. It has been and is used in other approaches and depending on the objective this subdivision can take various forms [21], [102]–[104].

Key structural elements required for the work of this thesis are the *elementary cell* and the *federation*. The key difference between the two types of elements is their temporal behaviour for the grid operation. *Elementary cells* are considered to be invariant for the grid operation, while *federations* have a dynamic aspect. This does not exclude the possibility that cells change as an result of reinforcement or grid reorganisation. But then they change due to external influences and not from an impulse coming from the grid operation. These two elements are introduced below. An extensive description enlarging the concept can be found in [D13], [99].

#### Elementary Cell

Manual switches are no active components for the automated grid operation that can only interact with remotely controllable switches (RCS). Based on this principle, the fraction of grid bordered by RCS is called an *elementary cell* or abbreviated *elementCell*. For the grid operation they are the smallest static entity and immutable by actions the grid operation can take itself. The example grid in Fig. 7.2 contains three *elementary cells*. These *elementary cells* play an important role when it comes to the reconfiguration of the grid, see Chapter 10. Depending on the size of these cells they might be operated by their own *cell DSO*. They then represent active elements. Otherwise they are used to structure the grid.

#### Federation

There might be several reasons why an *elementary cell* is not operated on its own. One is that the grid area belonging to an *elementary cell* might be too small to justify its own controller. This is especially true when the *elementary cell* contains few or no flexibility providing actor. And another reason is related to the fundamental laws of electricity. *Elementary cells* that are placed directly behind each other on the same feeder (as in Fig. 7.2 on the upper feeder), can not be operated independently from each other. The change of power flow in one cell, changes the power flows in the neighbouring cells. Thus, a constant exchange of information would be necessary. To overcome these drawbacks, several cells can be operated together and build so called *federations*. Such a federation can be only temporary to solve a specific problem or long-term. At the latest with the changing of the grid configuration through the activation of RCS, these *federations* come to an end. Responsible for the *federation* is always the *cell DSO* that initiated the building of the federation.

#### Substation Federation

One special case of federation is the consolidation of all *elementary cells* that are fed by one primary substation. They build together the so called *substation federation*. This federation is assumed to be long-term, only changing when the grid is reconfigured. Responsible for the secure operation of this federation is the *substation DSO*. The *elementary cells* of a *substation* *federation* might contain a *cell DSO* or *federation DSO*. In this case the *substation DSO* is the superior authority.

## 7.4 Actors and Functions

Some of the actors and roles of the grid operation have already been mentioned in the previous sections. They receive some further explanations in this section. In this text, the term “actor” does not refer to actual human beings but software components that act on behalf of someone or something. In its core the grid operation is designed as multi-agent system. It is further assumed that the actors run in devices installed in the grid area, so they are physically present. Together with the device hosting them they build a cyber-physical system. Theoretically this is not required, they could also run remotely on a server. But a lot of advantages of a distributed control like fast response time, reduction of communication or the possibility to build a microgrid - and that means most of the resilience capabilities - get lost when migrating the software into remote servers.

Main actors for the grid operation are the *DSO agents*, the local representatives of the DSO. They are either *cell DSOs* if they are responsible for an *elementary cell* or *substation DSOs* if they supervise a *substation federation*. Most of the new functions developed in this thesis are intended for them. Other actors like the *prosumer* or the *aggregator* are defined less in detail and implemented only as far as it was necessary to be able to test, simulate and validate the DSO-related functions. Other functions like the optimisation of self-consumption or portfolio management are not considered here.

#### Control Centre 

In a strict sense the control centre of the DSO is no active actor in the here developed grid operation, but is intended to allow the supervision of the grid state and operation by human beings. It further on servers as the overall coordinating entity that defines the parameters of the operation.

### *DSO agent*

The *DSO agents* are the major actors of the grid operation. Their core functionalities are given in the following list:

- Aggregation of measurements from the area of influence,
- State estimation of the grid state (see paragraph below) and bad data detection (Section 11.2.2),
- Analysis of of grid state (Chapter 8),
- Optimisation of grid state by the use of flexibility (Section 9.1),
- Validation of control signals by local measurements (Section 11.2.3).

Depending on the area of influence, the *DSO agent* is realised as *cell DSO* or *substation DSO*.

### Estimation of Grid State

The quality of the "view" which the *DSO agent* has on the status of the grid highly depends on the quality and number of available measurements. To have a full view on the grid one would require $2 \cdot n - 1$ measurements with $n$ the number of buses in the grid [105]. This is generally not available in the distribution grid. Adding new measurements is a question of money, and high quality measurements with high transfer rate are expensive. To a certain extend the use of state estimation methods can overcome this limitation. Power system state estimation is a method originally developed for the transmission grid to eliminate the measurements of defect sensors [105]. But with some modifications it can also be used in the distribution grid to compensate missing measurements [106]. The development of state estimation methods for the distribution grid is a very active field of research [106], [107]. As it is described in more detail in Appendix D.2.4, the state estimation used in this grid operation is implemented as classic weighted least squares state estimation according to [105].

### Substation DSO 

The *substation DSO* is the local representative of the DSO in the grid area fed by a primary substation. It is responsible for the secure and admissible grid operation in its *federation*. Periodically it analyses the grid state, optimises the operation and solves congestions. It can interact and coordinate with other *substation DSOs* and with subordinated *cell DSOs* to find solutions for constrained grid situations. For a lot of use cases developed in this thesis, this is the main actor. It is intended to be hosted in an IED in the primary substation.

Apart from the functions listed above for the general *DSO agent*, the *substation DSO* includes two further functionalities:

- Local control for substation transformer (Section 9.2.2),
- Self-healing after fault (Chapter 10).

### Cell DSO 

The *cell DSO* is the representative of the DSO within an *elementary cell*. A *cell DSO* would be hosted in a RTU or at a switchgear.

### Prosumer 

In contrast to other definitions, in this context a *prosumer* can be either a controllable load, or controllable generator or a combination of both. In the scheme in Fig. 7.2, a *PV prosumer* representing a PV system and a *load prosumer* representing a controllable load, are visualised. The main functionality with regard to the grid operation is to provide flexibilities for the *DSO agents*. They then change their behaviour according to a given set point. Flexibilities could be a range of reactive power values or a list of admissible charging powers for electric vehicles, see Table 4.1 for a comprehensive list of flexibility types considered in this work. One could imagine the smart meter as hosting device for the *prosumer*. Then the *prosumers* would also provide measurements for the *DSO agents*. To respect the unbundling they do not communicate with the *DSO agents* directly except for emergency cases and for possible measurements.

In summary, for the grid operation the *prosumer* contains the following functionalities:

- Provision of measurements,
- Provision of flexibilities,
- Adaption to set points,
- Local control (Section 9.2.1).

**Aggregator**

The *aggregator* is the guarantee for an unbundled system design. Its role is to aggregate the rather small scale *prosumers* and to represent them on the different markets and vis-à-vis the *DSO agents*. It can contain several functions like forecasting, risk and portfolio management, energy and capacity trading etc. In the context of the grid operation its main function is to collect the flexibility offers of the *prosumers*, to aggregate them and to provide them for the *DSO agents*. When the *DSO agents* want to impose a certain set point, this set point is transmitted via the *aggregator*, at least for the non-emergency cases. Thus the two main functionalities of the *aggregator* are:

- Aggregation of flexibilities,
- Transmitting of flexibilities.

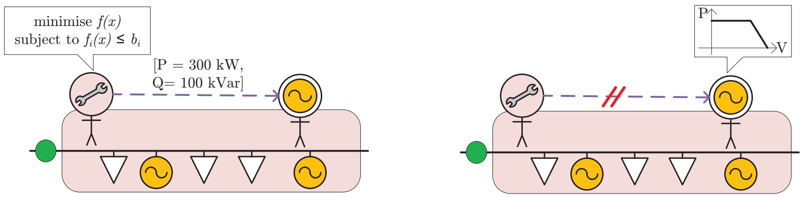
As in a deregulated energy market one can freely chose its electricity provider, one can imagine several *aggregators* where the *prosumer* can choose which it is assigned to. In contrast to the above mentioned actors, *aggregators* do not have a physical device attached. They could run in a server farm as pure software application or web-based service.

## 7.5 Interactions between Actors

Depending on the state and condition of the physical grid or of the actors of the grid operation, different types of coordination and interaction are realised between the actors of the grid operation. Thus, dynamically the distributed, hierarchical or even local characteristic of the grid operation is emphasised. Sometimes this dynamic changing of architecture is also called “heterarchy” [108]. This section introduces the three main transitions and interactions between the actors of the grid operation.

### 7.5.1 Distributed Coordination between *DSO agents*

It can happen that a *DSO agent* is not able to operate properly its particular grid area, e.g. because there are none or only insufficient flexibilities available. In this case it has the possibility to employ the distributed structure and the ability of the actors to dynamically interact. The affected *DSO agent* which can not solve the problem alone, can ask its neighbouring *DSO agents* to cooperate. That means that they dynamically join together to build a temporary unit, the *federation* introduced above. Natural leader of this *federation* is the *DSO agent* that initiated the process. This *DSO agent* then gathers all required information of the other participating *DSO agents* and coordinates the optimisation. After the problem is solved, the cooperation is broken up again. For example, this concept is realised for the extra-substation reconfiguration introduced in Section 10.2. Another way to handle the lacking of flexibilities can be to pass the command from the local *DSO agent* to a higher level agent, as it is described in the following section.




(a) Normal operation mode: optimisation of grid state by *DSO agent* and use of flexibilities of *prosumer*.

(b) Abnormal / emergency operation mode: local control of generators and transformers.

Figure 7.3: Local control as fall back strategy if the normal operation is not possible.

### 7.5.2 Hierarchical Coordination between *DSO agents*

The hierarchical interaction is mainly introduced to supervise the distributed operation and to intervene if necessary. To be able to do so, subordinated actors, like the *cell DSOs*, report regularly to their superordinated actors, in this case the *substation DSO*. They report especially if they take any corrective measures and why they take them. Based on this input, the superordinated actor decides whether or not to intervene. The classic case, demonstrated in Appendix C.3, is to detect "swinging" between the *cell DSOs*. In the design of the here presented grid operation, this decision is based on a set of rules, following the idea of an expert system. Other approaches like machine-learned decisions could be possible and more flexible. When intervening, this actor has a broader view on the system (including the neighbouring cells around the affected cell), other flexibilities at hand and can so try to find a more overall solution.

Another use of the hierarchical structure is if subordinated actors fall out. In this case the superordinated actor can temporarily take over the control until the outage is repaired. Thus, the hierarchy offers some inherent redundancy.

### 7.5.3 Local Control as Fall Back Strategy

The normal operation is always the control by *DSO agents* in the distributed way complemented by the possibility to interact in an hierarchical way. As it is discussed in the following chapter, this operation mainly consists in optimising the set-points of flexibilities. This behaviour is visualised in Fig. 7.3a.

This operation that always requires communication is completed by local control capabilities to build a comprehensive, robust and resilient grid operation. The local control is designed to build a fall back strategy for cases when the classic distributed-hierarchical operation is not possible; either because of outage or defect of the *DSO agent* or because of communication disruptions. In this case the local control methods help to support the grid operation, see Fig. 7.3b. Especially the Volt-Watt control as well as the frequency-Watt control, that are introduced in Section 9.2, are emergency response functions as they immediately react on critical situations. They are fall back strategies especially in the time domain, as they can react much faster than any optimisation.

The authors of [109] propose another approach, combining local droop control of distributed generators to support the grid with a central optimisation that optimises the droop parameters and regularly updates them.

# PART III

# METHODS FOR RESILIENT GRID OPERATION

# CHAPTER 8

# Coordination of Methods

In the previous part of this thesis the choice of architecture for the grid operation is motivated and introduced. This part is about the methods and functions especially designed for this operation architecture. It starts in this chapter with the core coordination methodology and key concept that guides the automated operation and decision making of the actors in the grid operation. For this, Section 8.1 introduces the idea of the power system traffic light and operation states and how this idea is used as basis to schedule functions of the grid operation. Section 8.2 then goes into detail on the design and development of the main supervising and control routine.

## 8.1 Power System Traffic Light

The idea of operation states for the operation of the power system is not new. It is especially used to describe the actions to be taken when contingencies appear in the grid [110]. In this thesis, the idea is combined with the so called **power system traffic light**. The power system traffic light is the core concept to coordinate the behaviour and actions of the grid operation. It is developed based on the roadmap proposed by the BDEW, the Federal Association of the German Energy and Water Industry, to implement smart grids in Germany [111]. This document, and especially the introduction of the so called "Ampelkonzept" (traffic light concept) to regulate the interactions between market and grid, led to broad scientific discourses in Germany. The work presented in this section, and previously published in [D2], [D3], contributes to this discourse. It proposes a realisation of the traffic light concept specialised for the distributed grid operation architecture introduced in the previous chapter. It combines the idea of different operating states of the grid operation with changing regulatory conditions depending on the phase of the traffic light. Additionally, it coordinates the rights and functions of the grid operation and chooses the appropriate method under varying conditions.

The power system traffic light defines possible operation states of the grid operation according to the phases of a classic traffic light: green (normal operation), amber (critical operation) and red (emergency operation) [70]. Additionally, the "outage" phase is introduced, after the grid suffered from a fault. Fig. 8.1 gives an overview over the phases of the power system traffic light.

In the **green phase**, the normal mode when operating the power system, no critical system states or violations of threshold values occur in the particular grid area (*cell* or *federation*). This phase defines a market dominated operation of the *prosumers*. The energy contracts placed by them via the *aggregators* for day-ahead or intra-day are valid without limitation. The real-time control of the *DSO agents* supervises and evaluates the system continuously but does not interact with the power flows. According to [70], [111] this does not exclude the use of classic operating reserves, like primary reserves traded on (trans)national levels. It also does not exclude the use of automatic tap changing transformers that use the voltage level directly behind the transformer. But no flexibilities as introduced in Section 4.6 are deployed.

At the other end of the power system traffic light, in the **red phase**, also called the emergency mode, the grid is in imminent danger. The actions taken in the red phase can repeal

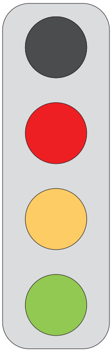



Figure 8.1: Phases and actions related to the power system traffic light; inspired by [70], [111].

market decisions and the *DSO agents* can directly act on the power flows and enforce certain behaviours, e.g. to disconnect distributed generators or loads. This phase is in line with §13(2) of the German "Energiewirtschaftsgesetz" (energy industry act).

A special phase is introduced by the **outage phase**, in which an outage already occurred in the grid (mainly due to failures). This phase requires the self-healing of the grid that resupplies as many loads as possible.

Between the green and red phase there exists a transition phase, similar to the **amber phase** in classic traffic lights. This phase describes the critical mode, where the first safety margins are violated, but without direct danger for the grid operation - this would be the red phase. The real-time strategies activated in this amber phase use the local market flexibilities provided by the *prosumers*. But also flexibilities that arise from the grid itself can be applied. The use of these flexibilities is optimised according to the situation and the preferences of the DSO. A forced intervention of the *DSO agents* apart from the use of flexibilities is not intended in this phase. This amber traffic light phase can be different depending on the part of the grid. Theoretically each *elementary cell* could be operated separately. Therefore, there exist not one power system traffic light for the entire grid but one for each *DSO agent*.

The control methods developed in the following chapters can be mapped on the phases of the traffic light: the optimisation for the red and amber phase is described in Section 9.1, the local control for the red phase in Section 9.2 and the self-healing for the outage phase is the subject of Chapter 10.

## 8.2 Implementation of Power System Traffic Light for *DSO agents*

This power system traffic light introduced in the previous section is the key part of the main supervising and optimisation procedure of the *DSO agents*. This procedure is executed every time step. The duration of these time steps can be chosen freely, this work suggests 10 min to 15 min. The 10 min to 15 min time step is a compromise between several aspects. On the one hand, the shorter gets the time frame, the more sure one can be to react on sudden changes. On the other hand, increasing communication capabilities are required. Renewable energy resources like wind or PV systems have problems to forecast their generation a long-time in advance. But some forecast is required if the device wants to propose flexibilities for the future. Thus 10 min to 15 min represent a reasonable time frame in which also simple forecast methods should achieve an acceptable accuracy. Also, there exist flexibilities, like heating or combined-heat and power units that should not be switched on and off too often. A reduction of the time steps length could lead to undesired frequent modifications in the operation of these devices. Finally, 15 min is the shortest time period for intra-day auctions on the European Energy Exchange. So the work of this thesis is in line with current market mechanisms. Finally, the 10-minute average value of the voltage is an important size for the power quality [112]. But to overcome the limitation with regard to sudden changes in the grid state, measurements are generally taken more frequently than just every 10 min to 15 min. These measurements are quickly checked. If they change dramatically, the regular operation is interrupted and additional methods are taken, like for example the self-healing after fault.

Fig. 8.2 gives the timeline and the overview of actions that are performed during one time step. This figure gives a general overview, omitting implementation specific aspects. A detailed UML sequence diagram of the steps required for the solving of an “amber” voltage profile violation can be found in Fig. F.1 in Appendix F.

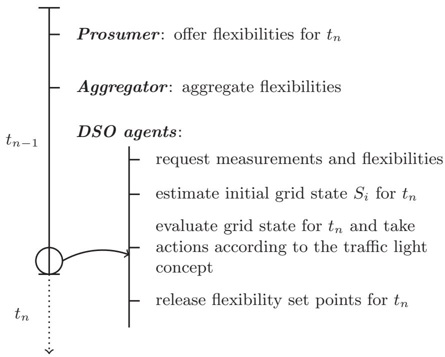



Figure 8.2: Timeline with actions to be taken within one time step.

In preparation for the following time step $t_n$, during the actual time step $t_{n-1}$ the *prosumers* provide their real-time flexibilities for time step $t_n$ to their *aggregators*. These offers of real-time flexibilities are always valid for exactly one time step, in which they can be used by the *DSO agents*. That means, flexibilities proposed by the *prosumers* for $t_{n-1}$ will not necessarily be available in $t_n$, and the flexibilities used in $t_{n-1}$ will no longer influence the grid in $t_n$.

Prior to time step $t_n$, at the very end of $t_{n-1}$, the *DSO agent* receives grid information from all the measurement points. Based on these measurement points the grid state is estimated see Section 7.4. As the *DSO agent* knows which flexibilities were used in $t_{n-1}$ their influence can be subtracted in the state estimation. This provides an initial estimated grid state $S_i$ at the beginning of $t_n$. This is the state of the grid at the beginning of $t_n$ if the *DSO agents* would not take any actions. This analysis just prior to the start of $t_n$, and before the influence of the flexibilities used in $t_{n-1}$ ceases, allows for a smoother transition between the time steps.

The resulting initial grid state $S_i$ is analysed concerning voltage profile violations at the buses of the grid and congestions on the grid lines. For system limit violations, two thresholds are defined: a critical limit $L_{\text{amber}}$ and an emergency limit $L_{\text{red}}$. The value of $L_{\text{red}}$ represents a threshold where a violation can lead to severe and imminent danger for the grid. The lower limit $L_{\mathrm{amber}}$ is used to trigger the start of the grid management intervention to avoid violation of $L_{\mathrm{red}}$. $L_{\mathrm{amber}}$ can be chosen according to the preferences of the DSO. $L_{\mathrm{red}}$ is assumed as a regulatory limit, as the violation of this limit authorises the *DSO agents* to suspend market mechanisms and to massively intervene in the grid.

### 8.2.1 Green Phase

The system stays in the **green phase** for as long as the analysis of the initial grid state $S_i$ does not show any violation of threshold $L_{\mathrm{amber}}$. After this analysis, the *DSO agent* does not take any further actions in this time step. Consequently, none of the market flexibilities provided by the *prosumers* and proposed by the *aggregators* are used.

### 8.2.2 Amber Phase

But if at least one bus voltage or one line current of $S_i$ exceeds the limit $L_{\mathrm{amber}}$ the *DSO agent* responsible for this part of the grid transitions into the **amber phase**. The *DSO agent* performs an optimisation to improve the grid situation. Inputs for this optimisation are all grid flexibilities as well as the market flexibilities provided by the *prosumers*. The optimisation method developed in this work is based on a meta-heuristics approach and is introduced in Section 9.1. The solution of this optimisation is a list of set points for the flexibilities provided by the *prosumers*, and set points for the grid flexibilities. These set points take effect at the beginning of the upcoming time step. Ideally, in the resulting grid state after the optimisation $S_r$ all system parameters respect the limit $L_{\mathrm{amber}}$. But this is not guaranteed, however $S_r$ should always be better than the initially computed state $S_i$. Otherwise the optimisation does not work correctly. But respecting $L_{\mathrm{amber}}$ after the optimisation does not change the grid phase back to green. The phase remains amber as flexibilities for the grid optimisation are used.

### 8.2.3 Red Phase

The **red phase** is triggered when at least one bus voltage deviation or one line current exceeds the emergency limit $L_{\mathrm{red}}$. In this phase, it is very important to bring back the grid into a non-constraining, secure and stable state as fast as possible, even if this results not in the theoretically best possible solution.

This can be achieved with a simplified optimisation that is based upon the same method as for the amber phase but stops its execution as soon as a “sufficient” solution is found. In addition, the complexity of the optimisation is reduced. Although the optimisation in the red phase is probably not the optimal one, it guarantees that solutions always eliminate the violations of $L_{\mathrm{red}}$. Otherwise an alert is given. Another important difference to the amber phase is that not only the flexibilities voluntarily provided by the *prosumers* can be used but all clients in the grid. To avoid disturbances to critical consumers - like hospitals etc. - as much as possible, each client can have a priority indicator assigned to it. This priority indicator is considered by the optimisation, leaving clients with a high priority indicator untouched. In addition to that, further functions become available in the red phase. It is the local reaction of the *prosumers* to locally detected problems. Each *prosumer* has a fall-back strategy implemented that describes its behaviour when it encounters a certain degraded grid state at its point of common coupling, see Section 9.2 for details. This function is important as it guarantees a certain behaviour in the case of communication problems and severe situations that do not leave any time to wait for the signal of the *DSO agent*.

With beginning of time step $t_n$, the flexibilities that were used in $t_{n-1}$ end, and possible flexibilities of $t_n$ are activated at the same time, based on the analysis and actions of the *DSO agent*. The resulting grid state $S_r$ at the beginning of $t_n$ may therefore not be equal to the initial estimated grid state of the time step $S_i$ as it is altered by the influence of the used flexibilities. In [D3] and [D2], the author of this thesis gives schematic visualisations of the transition between the phases.

### 8.2.4 Interactions between Actors

The traffic light phase defines not only the internal behaviour of actors as described in the sections above, but also changes the way in which the actors interact as described in Section 7.5. For example, in the amber phase the *DSO agent* transfers optimised set points to the *aggregator*, who de-aggregates them and hands them over to the *prosumers*. This communication path is the preferred one, as it respects the unbundling of grid and market. Nevertheless, in an emergency situation (red phase) it is important for the *DSO agents* to have direct communication possibilities with the *prosumers* and to be able to impose a certain behaviour directly on them. In Fig. F.2 in Appendix F this is visualised with an UML sequence diagram.

# CHAPTER 9

# Multi-Purpose Control Strategies

In the previous chapter, the power system traffic light and its phases green, amber and red have been introduced. As it is described in Section 8.2, in the amber and red phase the grid operation applies control strategies to react on the deteriorated grid state. These strategies mainly choose the appropriate reaction that would solve the violation of operation limits. The standard way to choose the best suited flexibilities is to perform an optimisation. For this a heuristic and multi-dimensional optimisation has been developed and implemented. This is described in Section 9.1 of this chapter. Additionally, local control strategies are provided as a complementary way to respond to critical grid states. They are introduced in Section 9.2.

The development of the heuristic multi-dimensional optimisation as suitable optimisation method for especially deteriorated grid states and its combination with local control strategies is one of the major scientific outcomes of this thesis (**scientific outcome 4** in list of Chapter 3).

## 9.1 Heuristic Multi-Dimensional Optimisation

In classic control centres, the operation of the power system is optimised by solving an optimal power flow (OPF) problem. Generally the objective of such an OPF is to minimise the operational costs, while at the same time respect the regulatory and physical constraints of the power system [90]. The OPF problem is generally a non-linear non-convex optimisation problem that can contain discrete and continuous variables [113]. In [90], [91] the authors review a list of mathematical techniques to solve the OPF problem until the year 1993. This list includes linear, quadratic and nonlinear programming, Newton-based approaches, mixed integer programming and interior point methods.

Also meta-heuristics like genetic algorithms, simulated annealing or particle swarm optimisation are used to solve the OPF [113]–[115]. The advantages are that non-linearities, the non-convexity and the mixture of discrete and continuous variables do not need to be approximated. While classic approaches rely on gradient based information, they tend to find local optima. Meta-heuristics on the other hand have a more global view on the problem and are more invariant to the initial values [116]. But they come with the disadvantage that the optimality of the solution can not be guaranteed. Further on, practical implementations have shown that these approaches often do not scale advantageously with large problems [113].

There exist also approaches to solve OPF related problems completely without a central calculation unit, relying on the coordination between different actors in the power system [117], [118]. Although they are very interesting from a scientific point of view, distribution system operators (DSOs) generally do not agree with the idea to optimise the grid by devices they can not control.

The objectives for the development of the optimisation method in this work are to create a multi-purpose optimisation that can solve typical problems that might appear in the distribution grid. Further on, it should be able to handle all different types of flexibilities and associated price curves. It should also be able to include continuous as well as discrete control variables and it should not require special considerations for the initial values. It also should be able to handle especially deteriorated grid states, where no strict solution that respects all constraints exists. In this chase it should be able to provide the best possible solution. These points are indicators for a heuristic approach. Given the distributed grid operation architecture, the respective parts of the grid that are optimised by one optimisation are rather small. This avoids the above mentioned limitation with regard to the grid size.

Eventually, as meta-heuristic optimisation technique the particle swarm approach is chosen. Section 9.1.1 introduces the idea of particle swarm optimisation, explains why this technique is chosen and shows its previous application in power system related problems. Section 9.1.2 gives the mathematical equations and parameters of the optimisation technique and Section 9.1.3 details the abort criteria of the optimisation. The aggregated fitness functions is described in Section 9.1.4. In Section 9.1.5 several test cases compare the behaviour of the here developed optimisation with a popular OPF solver. The work presented in this section relies on work already published in [D4].

### 9.1.1 Particle Swarm Optimisation in Grid Operation

Particle swarm optimisation (PSO) is a meta-heuristic optimisation algorithm inspired by flocks of birds and schools of fish [119], and was first proposed in 1995 by J. Kennedy and R. Eberhart in [119] and [120]. The authors of [121] give an overview over the use of PSO in power system related applications until the middle of 2005. Newer work also exists, e.g. [115], [122], [123].

In [124], a comparison of different meta-heuristic optimisation methods is done. The approaches particle swarm optimisation, ant colony optimisation, genetic algorithms, and simulated annealing are implemented to control the voltage of a distribution grid by the use of flexibilities. The author of [124] concluded that PSO is both the fastest method and finds the best results. The work of this thesis relies on previous work done by Diwold et al. that implements a PSO to realise the voltage control in a distribution grid [122]. But among other aspects, the work of this thesis extends this work by considering also the loading of lines and transformers as well as the inclusion of active power flexibilities.

In the grid operation of this work, the PSO is used by the *DSO agent* to optimise multiple criteria like the minimisation of voltage profile violations and congestions of lines and transformers as well as reactive power flows. As described in Section 8.2 this is coordinated by the power system traffic light and happens in near real-time, immediately after a problem or deviation from the nominal value has been detected.

The control variables and their possible co-domain that span the search space are given by the set points of flexibilities provided either by *prosumers* or active grid components. This includes DER units like PV systems, biogas plants and small wind generators but also controllable loads and storage. The types of flexibility that can be provided by *prosumers* are the active power injection or consumption $P$ and capacitive or inductive reactive power $Q$. Some facilities can provide both $P$ and $Q$ flexibility and sometimes, e.g. for PV systems, the maximal reactive power output depends on the actual active power set points. Set points of flexibilities can be continuous (e.g. reactive power provision of PV systems) or discrete (e.g. switching on or off of loads). To handle the latter in the PSO, they are treated like continuous variables, but are remapped on discrete values after each iteration. Other types of flexibilities can be provided by the grid itself, e.g. the tap position of an on-load tap changer (OLTC). Each of the possible flexibility set points has an associated cost. Furthermore, these set points (and their respective prices) are assumed to be valid for ten minutes into the future.

### 9.1.2 Mathematical Basics of Particle Swarm Optimisation

A PSO consists of a *swarm* of *particles* moving within a $d$-dimensional search space. The dimension depends on the number of control variables of the optimisation problem. Each position $\vec{x}^k$ of such a particle at time step $k$ can be a solution that optimises a given objective function. The position is a vector with $d$ elements, one for each control variable. In the context of evolutionary algorithms the objective function is also called *fitness function*. The direction and magnitude of the movement is influenced by the inherent velocity of the particle, the particles previous best position and the best position of a number of *informants*. Informants are other particles that exchange information and influence each other in the search. Mathematically, the velocity of each particle is defined componentwise for each dimension $j$ at each iteration $k+1$ according to

$$v_j^{k+1} = a_1 v_j^k + a_2 \left(p_j - x_j^k\right) + a_3 \left(g_j - x_j^k\right) \tag{9.1}$$

and its position is updated to

$$x_j^{k+1} = x_j^k + v_j^{k+1} \tag{9.2}$$

for all $j = 1, \ldots, d$ dimensions. The coefficients $a_1, a_2, a_3 \in \mathbb{R}$ are explained below. In each iteration $k$ the current velocity $v_j^k$ of dimension $j$ of a particle, its own best known position $p_j$, and the best position known by a certain number of informants $g_j$ are combined with certain coefficients $a_1$ to $a_3$, which describe the confidence in the three distinct parts of the velocity. The coefficient $a_1$ values the confidence of the particle in its own movement, $a_2$ the confidence of the particle in its own hitherto best position and $a_3$ the confidence in the best position of one of the particles informants. The ideal number of informants is problem dependent. In this work, according to the suggestions given by the author of [125], each particle has three informants. These informants are randomly selected. While $a_1$ is chosen a-priori, $a_2$ and $a_3$ are chosen from a uniform distribution over $[0, a_{\max}]$. Empirical studies given by the author of [125] show that for general optimisation problems, the choice of $a_1 = 0.7$ and $a_{\max} = 1.43$ yields good results (in terms of both quality and convergence rate).

After the new positions have been calculated according to Eq. (9.2), for discrete set points the positions need to be mapped on the list of possible set points. This is done with a simple up or down rounding on the closest available discrete value.

For each new position of a particle, the objective function described in Section 9.1.4 is evaluated and the values of $\vec{p}$ and $\vec{g}$ are updated if better results are identified. This process is repeated until one of the abort criteria described in Section 9.1.3 is reached. For a comprehensive introduction into the concept of PSO and more details on the parameter choice see [125].

### 9.1.3 Abort Criteria

To end the optimisation, three abort criteria are realised. As soon as one of these criteria is met, the optimisation stops and the position of the overall best particle of the swarm is returned as solution. The three criteria are:

- The number of iterations exceeds the maximal number of allowed iterations.
- The maximal velocity in the swarm is lower than a given threshold (that means all particles have converged around one position).
- The best fitness is not improved for a certain number of iterations.

Especially the last criterion can lead to a premature abort of the optimisation but helps to reduce the number of iterations significantly.

### 9.1.4 Fitness Function

As the particles move through the search space during the optimisation, their positions, i.e. the set points of the flexibilities, must be evaluated to allow an assessment of the solution quality. This is done with the Weighted Aggregation technique that is commonly used to treat multi-objective behaviour in optimisations [126]. The objective of the optimisation is to minimise the fitness function $f$, where multiple, possibly competing objectives are represented by different terms

$$f = f_V + f_I + f_{\text{price}} + f_Q. \tag{9.3}$$

The terms $f_V$ and $f_I$ penalises inadmissible voltage deviations and exceeding currents respectively. As the use of flexibilities is not free of charge, only the necessary amount of flexibilities should be used, and the cheapest ones should be used first. This is taken into account by the term $f_{\text{price}}$. Reactive power flows are minimised by the term $f_Q$.

The individual terms $f_{\text{X}}$ of the fitness function can be of completely different orders of magnitudes as well as different units. They are therefore normalised and scaled

$$f_{\text{X,norm}} = f_{\text{X}} \cdot \frac{f_{\text{X,weight}}}{f_{\text{X,max}}}. \tag{9.4}$$

$f_{\text{X,weight}}$ describes the reference point and the desired scale of the fitness parameter. $f_{\text{X,weight}}$ can be chosen according to the weight one wants to assign to the particular parameter. This freedom is one of the advantages of this heuristic optimisation as it allows the definition of "weak constraints". For example depending on the weighting, voltage profile violations that do not exceed a certain value are not corrected at all costs, but only in relation to a certain flexibility price. Disadvantage is that the weighting need to be chosen with deliberation, otherwise the optimisation does not find the intended solutions.

$f_{\text{X,max}}$ describes the maximum possible value of this parameter. This value is highly depending on the grid area, and there are functions included, see Eq. (9.12) - (9.15), to provide estimated upper limits for these parameters in a particular grid. In the following, the terms of the fitness function are described more in detail.

#### Voltage Profile Violation

Analysing all $n$ buses of the grid, $f_V$ is calculated according to

$$f_V = \frac{1}{n} \cdot \sum_{i=1}^{n} c_{V_i} \cdot \left(V_i - V_{\text{ref}}\right)^2, \tag{9.5}$$

with $V_i$ the magnitude of the voltage at node $i$, and $V_{\text{ref}}$ the reference voltage magnitude. $V_{\text{ref}}$ is generally chosen to be 1 p.u.. The coefficient $c_{V_i}$ is chosen to be not constant but incrementally increases as the voltage deviation from the reference value $V_{\text{ref}}$ reaches either the upper $V_{\max}$ or lower $V_{\min}$ limit. And it is zero if the voltage $V_i$ at bus $i$ is within certain boundary margins

$$c_{V_i} = \begin{cases} 0 & |V_i - V_{\text{ref}}| < |V_{\text{min,max}} - V_{\text{ref}}| \cdot \frac{1}{2} \\ 5 & |V_{\text{min,max}} - V_{\text{ref}}| > |V_i - V_{\text{ref}}| \geq |V_{\text{min,max}} - V_{\text{ref}}| \cdot \frac{1}{2} \\ 10 & |V_i - V_{\text{ref}}| \geq |V_{\text{min,max}} - V_{\text{ref}}| \end{cases}. \tag{9.6}$$

If $V_i$ is smaller then $V_{\text{ref}}$ then $V_{\min}$ is chosen in the above given equations, otherwise $V_{\max}$. The term $f_V$ as well as all other terms contributing to the fitness function are divided by the number of buses $n$. This makes them independent from the number of nodes in the grid, i.e. the grid size. The squaring of the summands $(V_i - V_{\text{ref}})$, as it can be seen also for the other terms of the fitness function, leads to a fitness function that is a combination of convex terms.

### Congestion

For each of the $m$ lines and transformers in the grid area, the current magnitude $I_i$ has to be smaller than a defined maximal value $I_{\max,i}$, which can differ from line to line and from transformer to transformer. The contribution to the fitness function is calculated according to

$$f_I = \frac{1}{n} \cdot \sum_{i=1}^{m} c_{I_i} \cdot I_i^2. \tag{9.7}$$

As described above for the coefficient regarding voltage profile violations $c_{V_i}$, the coefficient $c_{I_i}$ increases incrementally as the current approaches its critical limit

$$c_{I_i} = \begin{cases} 0 & I_i < I_{\max,i} \cdot 0.7 \\ 5 & I_{\max,i} \cdot 0.85 > I_i \geq I_{\max,i} \cdot 0.7 \\ 10 & I_i \geq I_{\max,i} \cdot 0.85 \end{cases}. \tag{9.8}$$

### Price of Flexibilities

The term $f_{\text{price}}$ adds up the price $p_i$ of the set point of flexibility $i$ for all $k$ applied flexibilities

$$f_{\text{price}} = \frac{1}{n} \cdot c_{\text{price}} \sum_{i=1}^{k} p_i^2. \tag{9.9}$$

The price for a flexibility $p_i$ varies with the actual set point of the flexibility and can have a quite complex behaviour. The coefficient $c_{\text{price}}$ is assumed to be constant with the value of 1. To get the relative figure, the term is divided by the total number of buses $n$ of the grid.

The choice of concrete flexibility costs is a difficult task as this depends on economic and regulatory considerations. This question is not further investigated here, but arbitrary values are chosen. Only several general rules are applied:

- the most expensive flexibility is the use of active power, either as increased/decreased load or increased/decreased generation,
- the reduction of injection of distributed generators is cheaper than the increase of injection of sources like batteries,
- the reactive power from distributed generators is much cheaper than any active power,
- and the activation of tap changers is the cheapest flexibility.

Appendix D.3.1 gives some more details about the implementation of different price functions.

### Reactive Power Flows

As reactive power can be easily and very cheaply produced by DGs that are connected to the grid via an inverter, the use of reactive power might not have a significant influence on the price term $f_{\text{price}}$, especially compared to the use of active power. Thus, an additional term $f_{\text{Q}}$ is introduced that penalises the injection of reactive power. This avoids solutions where there are two reactive power sources very close to each other and one produces a high $+Q$, while the other produces a high $-Q$. In summary, the term $f_Q$ acts as a regulariser to avoid unwanted solutions of spatially fluctuating reactive power. It sums up the squares of all the reactive power set points of all $k_Q$ reactive power flexibilities

$$f_Q = \frac{1}{n} \cdot c_Q \sum_{i=1}^{k_Q} Q_i^2. \tag{9.10}$$

The coefficient $c_Q$ is assumed to be constant with the value 1. Apart from this parameter that tries to minimise the overall reactive power, another approach can be considered. This is especially important if the investigated grid and the overlaying higher voltage grid are operated by different organisations. The reactive power flow at the point of interconnection of these two grids may be subject to contracts. That means, the reactive power flow from one grid to the other must be inside a certain margin. To accommodate this, an additional parameter can be included in the fitness function that penalises the deviation of the actual reactive power flow $Q_c$ at the point of interconnection $c$ from the admissible reactive power flow interval:

$$f_{Q_c} = c_{Q_c}(Q_c, Q_{\mathrm{min}_c}, Q_{\mathrm{max}_c}) \cdot \left(Q_c - Q_{\mathrm{ref}_c}\right)^2. \tag{9.11}$$

The coefficient $c_{Q_c}$ is zero as long as $Q_c$ lies within the interval and increases incrementally if $Q_c$ lies outside. $Q_{\mathrm{ref}_c}$ is defined as $Q_{\mathrm{ref}_c} = \frac{1}{2}\left(Q_{\mathrm{max}_c} + Q_{\mathrm{min}_c}\right)$, where $Q_{\mathrm{max}_c}$ and $Q_{\mathrm{min}_c}$ represent the lower and upper limit of the reactive power flow at $c$.

### Calculation of $f_{\mathbf{X},\mathbf{max}}$

To be able to normalise the terms of the fitness function according to Eq. (9.4) upper boundary values $f_{\mathrm{X,max}}$ are calculated before the optimisation. The following list describes the calculation.

- To get an upper limit for the voltage profile violations $f_{V,\mathrm{max}}$, it is assumed that on every node in the grid $i$, the voltage limit is violated in a way that in Eq. (9.6) the maximal value for $c_{\mathrm{V}}$ is chosen

$$f_{V,\mathrm{max}} = \frac{1}{n} \cdot \sum_{i=1}^{n} c_{V,\mathrm{max}} \cdot \left(V_{\mathrm{max,min},i} - V_{\mathrm{ref}}\right)^2. \tag{9.12}$$

- For the calculation of the upper limit of current congestions $f_{I,\mathrm{max}}$ an equivalent approach is taken, assuming that every line or transformer $i$ exceeds the maximal admissible current $I_{\mathrm{max},i}$

$$f_{I,\mathrm{max}} = \frac{1}{n} \cdot \sum_{i=1}^{m} c_{I,\mathrm{max}} \cdot I_{\mathrm{max},i}^2. \tag{9.13}$$

- The maximal price term per node $f_{\mathrm{price,max}}$ is calculated by summing up the squares of the maximum price every flexibility can cost

$$f_{\mathrm{price,max}} = \frac{1}{n} \cdot c_{\mathrm{price}} \sum_{i=1}^{k} p_{\mathrm{max},i}^2. \tag{9.14}$$

- And the maximal reactive power injection is calculated using the the maximum values $Q_{\mathrm{max}}$ of all reactive power flexibilities $k_Q$

$$f_{Q,\mathrm{max}} = \frac{1}{n} \cdot c_Q \sum_{i=1}^{k_Q} Q_{\mathrm{max},i}^2. \tag{9.15}$$

### 9.1.5 Comparison with Existing Approach

Appendix D.3.4 gives details on the implementation of the optimisation and the validation on a simple test grid. Further applications of the optimisation can also be found in Appendix C. The optimisation has also been tested in a field test set up. Details on these tests can be found in Appendix E.3.1.

The comparison with a prominent existing approach is done on the CIGRE benchmark grid, presented in Appendix A.2. Section A.2.1 in the same appendix gives the parameters and configurations of the grid and the *prosumer* flexibilities. In the following test case, the here developed PSO is compared against the popular OPF interior point solver of [127] in the pandapower environment [128].

#### Test Case 1: Low Load on CIGRE Grid

The first test case is done on the low load configuration of the CIGRE grid. The resulting optimised voltage profile is given in Fig. 9.1. As it can be seen, both optimisation approaches result roughly in the same voltage profile.

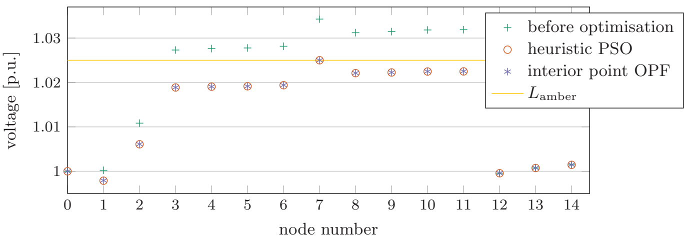



Figure 9.1: Voltage profile before and after the optimisations in low load situation on CIGRE medium voltage grid; the OPF is contributed by Friederike Meier, Fraunhofer IEE.

The OPF solution requires the injection of additional 496 kvar of reactive power, the PSO slightly less with 479 kvar. Thus, the quality of the solution is equivalent. The OPF can solve this problem only with quadratic price curves, as for piecewise linear functions, the solution would be near the discontinuities. The PSO can handle both types of price curves and is thus more stable with regard to its input data. However, the OPF is much faster (12 iterations that terminate within 0.5 s) than the PSO. The PSO requires between 400 and 800 iterations with a swarm size of 25. This takes 2 to 3 seconds. But the direct comparisons of time is doubtful, as the OPF is implemented in Python, the PSO in Java and no standardised real-time measurement is performed.

#### Test Case 2: High Load on CIGRE Grid

A second test case is done again on the CIGRE benchmark grid. But this time the high load situation is assumed. Further on, only reactive power flexibilities are considered, thus all *prosumers* listed in Table A.3 only provide reactive power flexibilities. The green plus signs in Fig. 9.2 give the initial voltage profile of the grid. For this situation the OPF in the given implementation of [127] does not converge and can not find a solution, as the reactive power alone is not sufficient to solve the voltage constraints everywhere in the grid. However, the heuristic PSO and the flexible aggregation in the fitness functions can make the most of the situation and can find a solution that nearly everywhere solves the voltage profile violations, except smaller deviations on several nodes. But for real word applications, this is absolutely sufficient. To be able to solve this problem with an OPF, its formulation would have to be adjusted, for example via the relaxation of hard constraints on the $L_{\text{amber}}$ boundaries. The results of this comparison in the two test cases above are in line with the findings proposed by other researcher on the comparison between OPF solvers and heuristic methods [116].

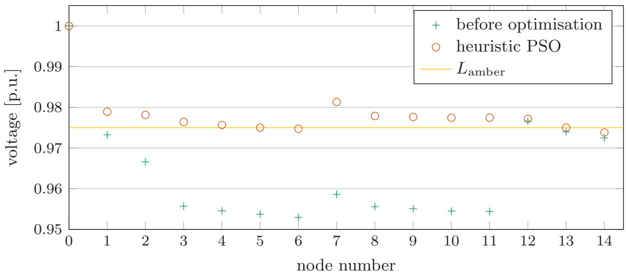



Figure 9.2: Voltage profile before and after the heuristic optimisation in high load situation; the OPF does not find a solution.

## 9.2 Local Control Strategies

As introduced in Section 5.2.2, local control refers to an architecture that does not involve any exchange of information between particular operation units. In Section 6.3 it is assessed that this type of control architecture is convenient for fast responses to local effects. It is also suitable for the realisation of fall back strategies in the case of communication interruptions or outages on the upstream operation layers. Additionally, it can also be considered as standard strategy for small scale *prosumers* that can or want not participate in the flexibility provision required for the optimisation introduced in the previous section.

In this work, two entities are considered to host local control functionalities. The first one are *prosumers* and in particular those that represent distributed generators. Section 9.2.1 introduces local control strategies for inverter coupled distributed generators like PV systems. Section 9.2.2 presents the local control for OLTC. All these strategies are not new. They are already state of the art or are on the verge of being part of the regulatory framework in some countries. New in this work is the deliberate combination of local control strategies with the above presented optimisation to build a resilient way to operate the grid. Details on this aspect can be found in Section 7.5.3.

### 9.2.1 Local Control of PV Systems

Local control of inverter coupled generators as it is regulated today aims to realise ancillary services to support the steady-state grid [129]. In which form this must be realised is defined in the grid codes for the medium and low voltage grid e.g. for Germany [130], [131]. Local control strategies are realised as additional control loop in the inverter. This control loop mainly uses continuous droop control and is realised as a combination of filters and loop feedback controllers.

Further details on the implementation of local control methods can be found in [84, p. 64-69]. Time constants are generally in the range of several seconds [84, p. 76].

The main purpose for this type of local control is the voltage support by reactive power provision. For this, all state-of-the-art control methods that are part of the regulatory framework in Germany have been implemented to be available for the *prosumers*. The details of the regulatory aspects can be found in [130], [131] and the acknowledged methods are: the fixed power factor $\cos\varphi_{\text{fix}}$, the Watt-Var control $\cos\varphi(P)$ and the Volt-Var control $Q(V)$. These methods are introduced in the following. As especially in the low voltage grids with high R/X ratio the voltage depends on the active power injection, the Volt-Watt control method $P(V)$ is also introduced. Apart from the voltage support, frequency support is an increasing issue, especially as action against over frequency. For this a frequency-Watt control method $P(f)$ is presented. Major parts of this section base upon the master's thesis of Franziska Meyer, supervised by the author of this thesis [D16].

### Fixed Power Factor $\cos\varphi_{\text{fix}}$

The most widely-used method at least in Germany is actually no control but a fixed parameter. To counteract the voltage rise due to power injection, the inverter adjusts its power factor $pf = \cos\varphi$ so that it behaves like an inductive load. The power factor $pf$ defines the portion between active and apparent power. It is equivalent to the cosine of the angle $\varphi$ between the complex voltage and current

$$pf = \cos\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}. \tag{9.16}$$

According to current regulatory conditions for the distribution grid in Germany, the DSO can choose the power factor from within a certain bandwidth. In the medium voltage grid as well as in the low voltage grid for systems with an apparent power smaller 13.8 kVA it can be chosen between $\cos\varphi_{\text{underexcited}} = 0.95$ and $\cos\varphi_{\text{overexcited}} = 0.95$ [130], [131]. For systems connected to the low voltage grid with an apparent power larger than 13.8 kVA the DSO can chose between $\cos\varphi_{\text{underexcited}} = 0.90$ and $\cos\varphi_{\text{overexcited}} = 0.90$ [130]. By using Eq. (9.16) the reactive power can be calculated depending on the active power output $P$

$$Q = P \cdot \sqrt{\frac{1}{\cos\varphi_{\text{fix}}^2} - 1}. \tag{9.17}$$

Thus the reactive power scales with the active power output. The disadvantage of this method is that permanently reactive power is injected into the grid, even if not required. This increases the technical losses and can lead to undesired reactive power flows to the higher voltage level.

### Watt-Var Control $\cos\varphi(P)$

To overcome the permanent injection of reactive power, the Watt-Var control method adjusts the power factor depending on the actual feed in power $\cos\varphi(P)$. The key assumption is that the higher is the active feed in power, the higher is the risk that over-voltages occur. Fig. 9.3 visualises an example characteristic of the relation between the relative power injection $\frac{P}{P_{\text{N}}}$ and the power factor. In this example, the power factor is reduced linearly if the actual power of the PV system $P$ exceeds a certain percentage of the installed power $P_{\text{N}}$. With this power factor $\cos\varphi(P)$ and by using Eq. (9.17) the reactive power can be calculated. This control method generally works only in one direction, reducing the effects of over-voltage.

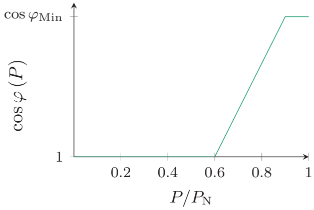



Figure 9.3: Watt-Var control $\cos\varphi\,(P)$ characteristic

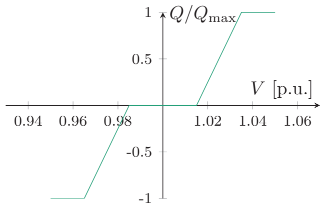



Figure 9.4: Volt-Var control $Q\,(V)$ characteristic

### Volt-Var Control $Q\,(V)$

The third method directly correlates the reactive power provision with the voltage at the point of common coupling of the inverter. Fig. 9.4 gives an example characteristic. Within a certain voltage bandwidth no reactive power is provided. Outside this bandwidth, the reactive power increases linear with the voltage. As can be seen on the symmetric form of the characteristic, this can also be used to increase the voltage in the case of under-voltage. Although this method is investigated since several years, and already mentioned in grid codes, it is not widely applied as there might exist stability issues [132].

### Volt-Watt Control $P\,(V)$

The three above introduced methods aim to support the voltage by providing reactive power. As already mentioned above, this might not be sufficient especially in low voltage grids, with an high ratio of R/X in the lines. Additionally, Volt-Watt control it is considered to be especially useful as fall back strategy for disturbed and emergency grid states [133]. The Volt-Watt control method considers the adjusting of the active power depending on the voltage at the point of common coupling. A possible characteristic is given in Fig. 9.5 that reduces the active power feed in linearly above a certain threshold. One could also imagine the increasing of active power feed in for situations with under-voltage. But this would require the permanent curtailment of active power. This method is not yet part of grid codes but is still investigated in research. The combined operation of Volt-Var and Volt-Watt control can lead to stability issues [134].

### Frequency-Watt Control $P\,(f)$

With the rising penetration of distributed generators their influence on the frequency increases. This is especially true for situations when the grid frequency exceeds the threshold values in the inverters and thus triggers the sudden and abrupt disconnection of all distributed generators. Therefore a droop characteristic is introduced not unlike the droop control that is realised in conventional bulk generators. Above a certain frequency, here chosen to be 50.2 Hz, the active power injection is reduced, following characteristics like the one given in Fig. 9.6.

### Comparison

The above introduced local control methods are available for the *prosumers*. Details on the implementation can be found in Appendix D.3.2.

Fig. 9.7 visualises the effects of the above introduced local control methods for voltage support. The basis grid is the low load snapshot of the CIGRE benchmark grid introduced in

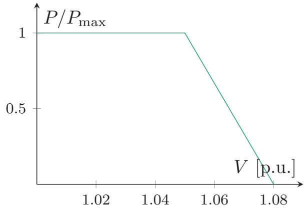



Figure 9.5: Volt-Watt control $P(V)$ characteristic

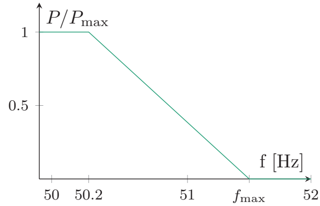



Figure 9.6: Frequency-Watt control $P(f)$ characteristic

Appendix A.2 and with the local control *prosumers* as given in Table A.4. The parametrisation of the local control methods follows the regulatory framework of Germany for medium voltage grids [131]. Without local control the upper amber voltage limit $L_{\text{amber}}$ as introduced

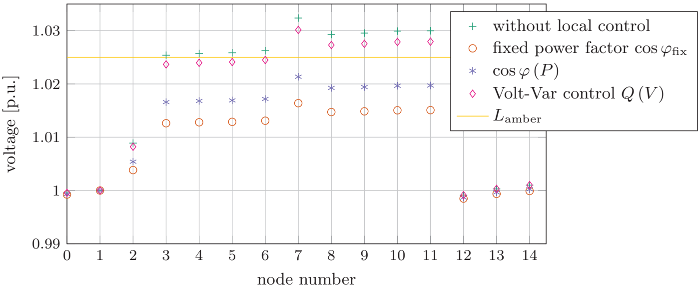



Figure 9.7: Comparison of voltage profiles of CIGRE benchmark grid low load situation with different local control methods.

in Section 8.2 is violated. The $\cos\varphi_{\text{fix}}$ as well as the $\cos\varphi(P)$ bring the voltage everywhere in the grid below this limit. But they create substantial reactive power flows and lead to voltage drops even in places where no violations occur. The Volt-Var control requires the minimum reactive power but might not bring down the voltage below the limit $L_{\text{amber}}$, at least for this test case. The Volt-Watt control is not visualised in the figure above. In the given parametrisation visualised in Fig. 9.5 this method starts to reduce the active power above the voltage limit of 1.05 p.u.. As this threshold is not violated, this method is not yet activated. Table 9.1 compares the required additional injection of reactive power caused by the local control methods.

Table 9.1: Comparison of required reactive power injection by local control methods.

| Method | Reactive power $Q$ [kvar] |
|---|---|
| fixed power factor $\cos\varphi_{\text{fix}}$ | 1052 |
| $\cos\varphi(P)$ | 729 |
| Volt-Var control $Q(V)$ | 135 |
| optimisation of Section 9.1.5 | 479 |

These values can be compared with the sum of the reactive power injection obtained by the optimisation of the same CIGRE benchmark grid low load configuration, see Section 9.1.5, of 479 kVar. This optimised value is larger than the reactive power injected by the Volt-Var control but fully eliminates the voltage profile violations. Compared to the method of fixed power factor and $\cos\varphi(P)$, the optimised solution shows the amount of reactive power overhead caused by these two approaches.

### 9.2.2 Local Control for Transformers

In the validation of the optimisation in Appendix D.3.4 the on-load tap changer (OLTC) is used as grid flexibility for the optimisation. But it can also be used in local control mode. For this, the voltage at the low-voltage side of the transformer is used as reference voltage. By changing the tap position, the transmission ratio between the primary high-voltage and the secondary low-voltage side changes. This allows the decoupling of the voltage level of the two sides up to a certain degree. The local control for OLTC is implemented as described in Appendix D.3.3 as an optional function for the *substation DSO*. It allows the control of the tap changers of the transformers of the particular primary substation belonging to the *substation DSO*. Appendix D.3.3 also gives an example simulation of the OLTC behaviour under local control.

## 9.3 Conclusion

This chapter presents the two main operation methods for the amber and red phase of the power system traffic light. This operation methods are especially designed to meet the requirements in the distribution grid and for a distributed architecture. This means that the optimisation is designed as a multi-purpose tool to solve automatically the typical problems that arise in the distribution grid.

The comparison with a standard OPF solver shows that the here developed optimisation finds at least results with equal quality. At the same time a higher degree of freedom in the formulation of constraints and price curves is possible. And solutions are found even for situations where classic OPF solvers do not converge. This is an important aspect for the design of resilient optimisation methods, because they should be able to propose the best solution for a deteriorated grid state, even if this solution does not respect all constraints. Although slower, the runtime of the heuristic optimisation is still acceptable for near real time use. But the result of the heuristic optimisation depends strongly on the relative weighting between the parameters of the fitness function. For this no absolute configuration can be given, but the desired behaviour also depends on the preferences of the DSO. Thus, the here presented optimisation could be combined with a calibrating phase, to defined the appropriate weighting.

The local control is designed as fall back strategy if the above described optimisation can not be applied. This local control strategies especially consider voltage and frequency issues and can react without further communication on deteriorations of the grid state.

# CHAPTER 10

# Self-Healing with Evolving Search Space

The medium voltage grid is often built in a looped or even meshed way, but operated in radial form, as it has been introduced in Section 4.1. By closing previously open switches (also called tie switches) and at another place open closed switches (also called sectionalising switches) the grid configuration can be changed. This process of establishing a new configuration, by opening and closing switches, based upon a given grid topology is referred to as reconfiguration of the power grid.

Reconfiguration in the medium voltage grid is mainly used for two purposes: for the optimisation of the operation conditions in the grid, and for the restoration of power supply after a fault. The here presented work focuses on the latter aspect, also referred to as self-healing capability. When the circuit breaker of a feeder in a primary substation is tripped after a fault in the medium voltage grid, sometimes a reclosing process tries to re-establish the supply. If the fault can not be cleared, a persistent physical damage exists. Then the DSO tries to re-establish the supply to the greatest possible extend by reconfiguring the grid. An interruption of clients that exceeds a certain time must be reported to the national regulating authority and might be followed by a penalty that has to be paid by the DSO [135], [136]. In countries like Germany and France that follow EN 50160 this time frame is three minutes [112]. Other standards like IEEE 1159 set this time frame to one minute [137]. This span constitute the optimal time frame in which a possible new grid configuration should be found and established. This implies that only remotely controllable switches (RCS) can be used for this action. The part of the grid that can not be resupplied before reparations must remain isolated. The smallest part of a grid that must remain isolated is what has been introduced as *elementary cell* (*elementCell*) in Section 7.2.

However, finding a new grid configuration represents a combinatorial, nonlinear, multi-objective optimisation problem. From its complexity, it is classified as a NP-hard problem, as Enacheanu showed in his thesis [138, p. 85-90]. Presently, this problem is not commonly solved following the fault, but the reconfiguration is often realised by using pre-calculated tables or solutions. But this very static approach has several draw backs: Historically, the tables are calculated in a maximum load situation, what previously was the worst case situation. But with the increasing introduction of fluctuating and renewable distributed generators (DG) and loads like electric vehicles the power flow pattern of a feeder of a distribution grid can vary tremendously according to meteorological circumstances and the time of day. The near real-time calculation on the other hand allows to find appropriate solutions with respect to the actual situation. This chapter proposes an evolvingly increasing and distributed reconfiguration approach specialised for the self-healing of the distribution grid. The goal is to realise a good solution within a limited time frame. The approach makes use of the distributed grid operation introduced in Section 7.2. It is a graph theory based algorithm that uses an evolvingly increasing search space to solve the problem after a fault has occurred. It is thus very flexible and scalable and it bases its solution on the current status of the grid. To establish a valid grid configuration that respects constrains it can further rely on flexibilities provided by controllable loads and distributed generators by reusing the optimisation proposed in Section 9.1.

This self-healing capability is an important aspect when it comes to the design of especially resilient distribution grids [19]. It belongs to the restorative capacities of a system, see Section 2.2.3. Its development is one of the major scientific outcomes of this thesis (**scientific outcome 5** according to the list given in Chapter 3).

This chapter is structured as follows: Section 10.1 summarises previous and related work on this field, Section 10.2 presents the overall concept of the self-healing approach. In Section 10.3 the methodology of the fault location, the generation of new grid configurations based on graph theory and the evaluation with a multi-objective fitness function is elaborated. The validation of the approach based on simulation is described in Section 10.4. Further on, the here presented approach is also compared against other types of self-healing approaches and investigated with regard to its resilience capabilities.

For the most part, the work of this chapter has been previously published in [D1].

## 10.1 Previous and Related Work

As has been mentioned above, the reconfiguration is a combinatorial, non-linear, multi-objective optimisation problem. In a grid with $n_\text{S}$ switches exist $2^{n_\text{S}}$ possible grid configurations. However, many of these possibilities can be discarded as they result in isolated nodes or loops [139]. Apart from the topological feasibility, each new grid configuration must be evaluated with regard to its technical constraints (e.g. voltage profile, currents). This part of the problem requires the solving of the non-linear power flow equations. A valid grid state is subject to multi-constraints, which can contradict each other [140].

### 10.1.1 Early Work

The beginning of the increased interest in near real-time reconfiguration methods coincides with the emergence of the first advanced controllers and the introduction of distribution system automation [141]. These first activities used the reconfiguration for loss reduction by transferring load from one feeder to another [141]–[144]. The main focus of these first approaches was the reduction of the computation time for the power flow by proposing suitable approximations [141], [143]. The authors of [142] start with a system where all switches are closed and then successively open the switches again until a radial structure is established. The work presented in [145] closes all switches on a loop and successively finds the best configuration for every loop. By relying on graph theory principles the work of this thesis combines the latter two approaches. Also the use of reconfiguration for the service restoration is investigated quite early [146], [147].

To overcome the combinatorial nature of the problem the authors of [148] transfer the discrete switches into a continuous function, and then solve the convex sub-problem. In the eighties, one important trend in computer science were so called expert systems that derived solutions to problems by relying on a "knowledge base" and by using a "inference procedure". An expert system that can also be used for the loss reduction through reconfiguration is proposed in [149].

Where classic optimisation methods struggle to find solutions, heuristics are sometimes a good choice. But one has to keep in mind that they can not guarantee that always the global optimal solution is found. Sometimes they only find a "good enough" solution. The authors of [150] present a heuristic search method to construct possible new grid configurations. And in [151], the authors compare some of the above mentioned works, and draw the conclusion that heuristic approaches are a very promising way to solve the reconfiguration problem.

### 10.1.2 Meta-Heuristics and Fuzzy Approaches

With the emergence of the ideas of meta-heuristic optimisation and the increasing computing power, the reconfiguration problem has been tackled by a variety of meta-heuristic approaches [152]. For example, simulated annealing is very suitable for the reconfiguration problem, as it is designed for combinatorial optimisation problems [153], [154].

Also genetic algorithms are very suitable for the reconfiguration problem [155]. In genetic algorithms, possible solutions are coded in so called chromosomes. The appropriate coding of the grid configuration into chromosomes is one of the major steps in the optimisation [156]–[158]. The later two approaches use the concepts of fundamental loops derived from graph theory for the generation of chromosomes. The binary version of particle swarm optimisation (PSO) is also successfully applied in [159] to solve the reconfiguration problem for the restoration of power systems after faults. In [160] the behaviour of PSO and genetic algorithms for the reconfiguration after faults is compared. Despite this multitude of approaches, meta-heursitics are not the best choice for real time applications because of their complexity [161].

Das in [162] applied fuzzy sets to model the objectives of the reconfiguration. The authors of [163] used a genetic algorithm together with the data of distributed generators (DG) for the reconfiguration to reduce losses.

### 10.1.3 Taking into Account Distributed Generators

The fluctuating and increasing injection of distributed generation into the distribution grid introduces further uncertainties into the reconfiguration problem. If the number of possible switching actions is restricted, the reconfiguration takes not only into account the current status bust must also consider probable forecasts of the electricity injection of DGs [164], [165]. In countries where the power system is not unbundled, the question of reconfiguration is combined with the question of where to optimally place distributed generators [166], [167]

### 10.1.4 Multi-Agent Systems

All the contribution mentioned above have one thing in common: They solve the reconfiguration problem in a central way. This changed in the work presented in [168]. It proposes a multi-agent system for the restoration after fault. Although agent-based, it is still very centralised around one specific agent. A fully decentralised approach is given in [169]. There, service is restored relying on the coordination between the agents. In [161], [170], the authors combine decentralised agents with a hierarchical coordination between the agents. Their approach also relies on graph theory concepts and optimises strongly coupled loops together. The approach of this thesis goes further by omitting the grid configuration in areas not related to the fault.

The work presented in [171] combines a multi-agent system with the use of machine learning approaches. Thus, solutions that have once been found with a genetic algorithm for a given fault can be reused. Especially with a high presence of DGs valid solutions for the same fault can vary considerably and replacing time consuming optimisations by machine learning can not always guarantee a good solution.

In [172], the authors give a comparison between centralised and distributed solutions for the service restoration. The approach developed in this thesis is a compromise between the fully distributed and the classic central approach. It is oriented on the already available devices in the grid, and can be seen as an extension of intelligent electronic devices (IED).

## 10.2 Self-Healing Concept

The self-healing approach of this work relies on the distributed control structure introduced in Section 7.2, and again visualised in Fig. 10.1. Key concept is to keep the reconfiguration as local as possible, and thus significantly reduce the search space. While this approach might not lead to a globally optimal solution, it does vastly improve the computational feasibility.

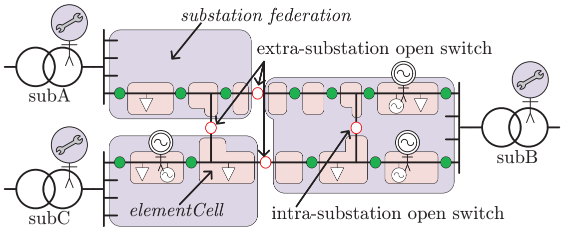



Figure 10.1: Visualisation of major elements and actors of the distributed grid operation required for the self-healing.

When a permanent fault appears on a feeder in the radial distribution grid, the protection that is normally placed on the feeder in the primary substation activates and trips the circuit breaker. This results in a fully unsupplied feeder, see Fig. 10.2. The first step is to identify the faulty *elementCell*, by analysing the signals of the fault passage indicators (FPIs), see Section 10.3.2.

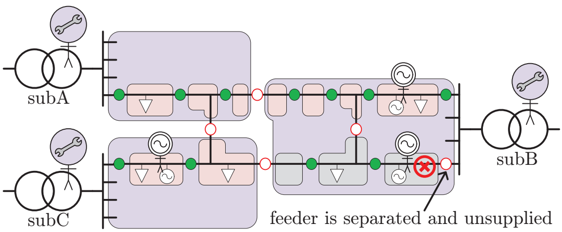



Figure 10.2: Fault on second feeder of subB leaves the whole feeder unsupplied.

Then the *substation DSO* of the primary substation that supplies the faulty *elementCell* starts the process to find a new grid configuration. In the first step, it tries to find a new configuration within its own *substation federation*. This is done by using possible open tie switches that connect two feeders of the same substation. This part of the process is called **intra-substation reconfiguration**, and switches that connect two feeders of the same substation are called “intra-substation open switches”, see Fig. 10.1. If a valid solution can be found, the new configuration is established. The first step when doing this is always the isolation of the faulty *elementCell*. A possible solution is visualised in Fig. 10.3. As it is described in Section 10.3.5 the reconfiguration can be extended by the use of flexibilities.

The securing of one feeder by another of the same primary substation by simple loops is a common way to construct medium voltage grids. Thus, this possibility is checked first by the *intra-reconfiguration*. Additionally, the number of available RCSs scales with the number

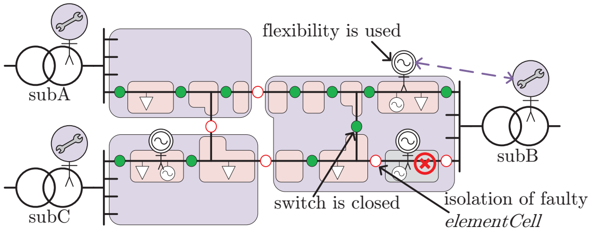



Figure 10.3: Intra-substation reconfiguration with use of flexibilities.

of feeders in the grid: In France there are on an average 2 RCS per feeder [101]. Thus from a combinatorial point of view, much less solutions are possible on a smaller grid that contains only one primary substation. Further on, this *intra-reconfiguration* does not require any communication with other *substation DSOs*, as all necessary information is already available.

If no valid solution can be found, or no intra-substation open switches exist, the *substation DSO* tries the reconfiguration with the securing substations. This is done in a peer-to-peer mode, with one securing substation at a time. This part of the process is called **extra-substation reconfiguration**, and the open switches that would connect two substations with one another are the “extra-substation open switches”. There might exist several securing substations, but not all of them provide a reconfiguration possibility for the part of the grid that is affected. A first test verifies, if the extra-substation open switches lead to new grid configurations that possibly could resupply the non-faulted parts of the feeder. This is tested based on a graph representation of the grid data and by analysing possible cycles of this graph as it is described in Section 10.3.1. Only those *substation DSOs* are contacted that pass this test.

Possible partner substations evaluate if they can participate in the reconfiguration or not. There might be reasons (like unstable operation state) that prevent a *substation DSO* from joining in. If a securing *substation DSO* agrees to participate, it provides the host *substation DSO* with all the necessary information like grid data, current grid state and available flexibilities. The host substation then treats the joint grid area as one. An example solution for this is visualised in Fig. 10.4.

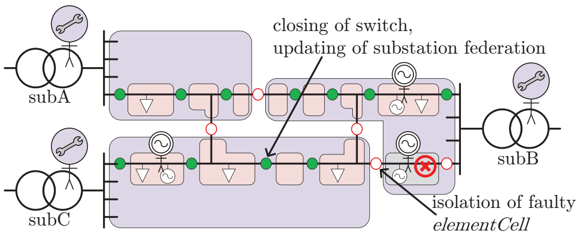



Figure 10.4: Result of the extra-reconfiguration between subB and subC.

As each *substation DSO* keeps a local record of the grid data of the *substation federation*, this data base needs to be updated after the *extra-reconfiguration*.

For a lot of cases the solutions of this approach will be sufficient until the fault is repaired. For the others, the new configuration can fill the time until a more “optimal” configuration is realised. For this a global optimisation including all securing substations can be used. Possible approaches are described in [D14].

# 10.3 Methodology

The previous section introduces the basic concepts of the proposed self-healing approach. The following sections focus on the different steps that are performed and provide an in-depth view of the mathematical and algorithmic description of the approach. The mathematical concepts do not differ between *intra-reconfiguration* and *extra-reconfiguration*, only the considered grid data does. Fig. 10.5 gives an overview of the steps.

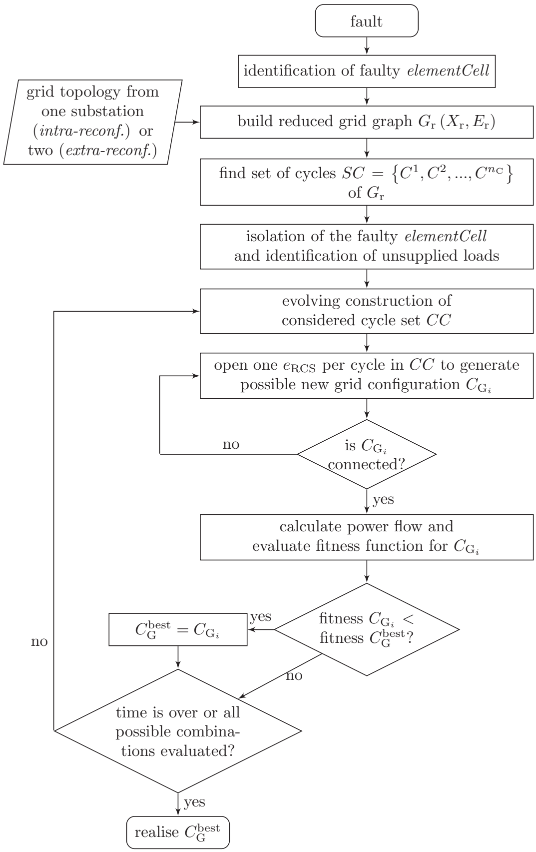



Figure 10.5: Overview of the self-healing methodology.

## 10.3.1 Required Graph Theory Concepts

A lot of tasks that need to be performed in the following can be simplified by making use of graph theory. The grid topology is therefore mapped to a graph $G\left(X, E\right)$, representing the buses as a set of nodes $X(G)$ and lines, cables and transformers connecting the buses as a set of edges $E(G)$ of the graph. Also switches are modeled as edges, connecting two nodes if and only if closed. A *path* on this graph is defined as the sequence of nodes $(x_0, x_1, ..., x_k)$ that are connected by a sequence of edges $(e_0, e_1, ..., e_{(k-1)})$ where the nodes are mutually distinct. Does one add another edge $e_k$ that connects the last node $x_k$ with the first one $x_0$, it results a *cycle* [173]. In the following, cycles are represented by the set of edges that build the cycle $(e_0, ..., e_k)$ with $k$ being the number of edges on the cycle. The topology of a grid can thus be represented as an undirected graph. In a connected graph, there exist a path between all nodes [173]. Assuming all switches are closed, the graph representing the grid is connected and likely to contain cycles. A graph without any cycles (also called acyclic) is generally a *forest*. A connected acyclic graph is called a *tree*. Trees are the structures that represent radial grids. After a fault, when the circuit breaker is opened, the graph is no longer connected, it becomes a forest. From a mathematical point of view, the reconfiguration problem consists in finding the spanning tree $T$ for the graph $G$ so that $T \subseteq G$ with $X(G) = X(T)$, with the restriction, that only some of the edges (the edges that represent RCS) can actually be removed from the graph. The spanning tree problem is common in many application (e.g. communication networks), especially the finding of a spanning tree that minimises the weights that might be assigned to the edges. Weights $v$ of edges can be integer or real values formally defined as $v : E \to \Re$. And there exist standard ways to solve such problems, e.g. the Kruskal's algorithm [174]. However, the reconfiguration problem has the complication that the edge weights would be non-constant. Instead, they would depend on the power flow, which in turn depends on the current grid configuration.

In the here presented work, the cycle definition is used to construct the spanning trees. Edges that are part of $G$ but not of $T$, $E(G) \setminus E(T)$, are called *chords* [173]. For the reconfiguration problem these chords, that means the switches that have to be opened, must be found. For this the definition of *fundamental cycles* is used: A connected graph $G = (X, E)$ has a spanning tree $T \subseteq G$ [173]. For each chord $e \in E \setminus E(T)$ there exists a unique cycle $C^{\mathrm{e}}$ in $T + e$ [173]. This cycle $C^{\mathrm{e}}$ is called *fundamental cycle* of $G$ to $T$ [173]. In [157], the same concept is also used as basis for the reconfiguration and called "fundamental loops".

From this, it can be derived that to construct all possible $T$ from $G$ exactly one edge has to be removed from every fundamental cycle $C^i$ of $G$. Or within the context of the power system: The number of cycles on the grid graph $n_{\mathrm{C}}$ must be equal to the switches that are open. With this concept, all possible $T$ can be constructed.

### 10.3.2 Fault Location

In the distribution grid, the general way to localise a fault is to use fault passage indicators (FPIs). For the self-healing only those combined with RCSs are used, but there might be more non-communicating FPIs available in the field. They are triggered when a fault current is detected. The fault location approach used here is taken from [175] and [D14]. Based on the grid configuration before the fault, the ideal response of the FPIs is calculated for each of the *elementCells* that can possibly contain the fault. This matrix of ideal responses $M_{\mathrm{IR}}$ contains in the rows all possible faulty *elementCells* and in the columns whether or not a particular FPI would be activated in the case of a fault in the specific *elementCell*, e.g.

$$M_{\mathrm{IR}} = \begin{bmatrix} & \text{FPI 1} & \text{FPI 2} & ... \\ \textit{elementCell}\ \text{a} & 0/1 & 0/1 & ... \\ \textit{elementCell}\ \text{b} & 0/1 & 0/1 & ... \\ ... & & & \end{bmatrix}. \tag{10.1}$$

$M_{\mathrm{IR}}$ is constructed using a Dijkstra's algorithm to find the shortest path from all *elementCells* to the supplying substation. The simplest approach after a fault would be to compare the activated FPIs with the matrix of the ideal responses and to identify the faulty *elementCells*. But this would mislead the localisation as soon as one FPI is not working correctly. So a more robust approach is developed, taking into account the probability $\alpha_i$, which is the probability that the FPI $i$ is activated and the probability $\beta_i$ that the FPI $i$ is activated correctly (so only activated if a fault is actually there). Based on these two probabilities the conditional probability of the fault to be localised in a certain *elementCells* given a sequence of activated FPIs, $P$ (fault in an *elementCell* | activated FPIs) can be derived by applying basic concepts of probability and the Bayes'theorem. Further information about the fault location and the detailed description of the conditional possibilities can be found in [D14].

The use of FPIs for the calculation of the location of the failure has one drawback: It can not be used for high resistive earth faults as their currents can not trigger the FPIs but only the circuit breaker is opening. Sometimes special earth fault indicators (EFI) are also installed, then they can be analysed. If this is not the case, the same approach must be taken that the operator would do manually in this case: To open all switches of the affected feeder and then starting from the substation on, to reclose the switches one after the other and test whether or not the circuit breaker is again tripped.

Having identified the faulty *elementCell* a new grid configuration can be searched that isolates this *elementCell* and resupplies as many loads as possible on the affected feeder.

### 10.3.3 Creating of New Grid Configurations

This section describes in detail according to which rules new grid configurations are generated.

#### Reduced Grid Graph

To generate new candidate grid configurations the topology of the grid area under investigation is transferred to what is called here a "reduced grid graph" $G_{\mathrm{r}}(X_{\mathrm{r}}, E_{\mathrm{r}})$ representation. As only RCS are considered as modifiable through the self-healing, one *elementCell* - that can contain up to hundred buses - can be reduced to only one edge $e_{\mathrm{elementCell}}$ in $G_{\mathrm{r}}$. For all questions with regard to the structure, $G_{\mathrm{r}}$ is still a valid representation of the grid, but with a significant reduction of number of nodes and edges. This is especially important for runtime. The RCS that connect the *elementCells* are modeled as the connecting edges $e_{\mathrm{RCS}}$ between the boundary nodes of the *elementCell*. In $G_{\mathrm{r}}$ all RCS, both open and closed, are represented. A record must be kept about which edges in $G_{\mathrm{r}}$ represent RCS and which edges represent *elementCell*. This is important as later on in the method only edges representing RCS can be opened. As described in Section 10.3.1, the resulting graph is a connected, undirected graph that should contain cycles, otherwise no reconfiguration can be applied.

#### Set of Cycles on the Graph

The final new grid configuration must no longer contain any cycles, it must be a tree. To establish this radial grid structure, for each cycle of the graph one chord has to be found and removed, this means a RCS has to be opened, as derived in Section 10.3.1. To find all cycles on $G_{\mathrm{r}}$, a cycle detection is performed according to [176], resulting in a set of cycles of the graph $SC = \{C^1, C^2, ..., C^{n_{\mathrm{C}}}\}$ with $n_{\mathrm{C}}$ the number of cycles on the graph. Each cycle $C^j$ can be defined by the list of edges that build it

$$C^j = \left(e_1^j, e_2^j, ..., e_k^j\right). \tag{10.2}$$

For each cycle, those edges $e_{\text{RCS}}$ can be identified that represent RCSs

$$C_{\text{RCS}}^{j} = \left(e_{\text{RCS}_1}^{j}, e_{\text{RCS}_2}^{j}, \ldots, e_{\text{RCS}_{n_{\text{RCS}}}}^{j}\right). \tag{10.3}$$

These are possible chords. Fig. 10.6 shows the reduced grid graph of an example grid. The set of cycles $SC$ for this grid contains $n_{\text{C}} = 4$ cycles.

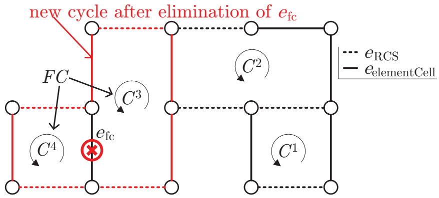



Figure 10.6: Example of a reduced grid graph $G_{\text{r}}$ including four cycles and the faulty *elementCell* represented by $e_{\text{fc}}$.

For an exhaustive search of all possible combinations to build a spanning tree for this graph by removing $e_{\text{RCS}}$, there would exist $n_{\text{Solutions}} = n_{\text{RCS}}^{1} \cdot n_{\text{RCS}}^{2} \cdot \ldots \cdot n_{\text{RCS}}^{n_{\text{C}}}$ possible new configurations, with $n_{\text{RCS}}^{j}$ the number of RCS on cycle $C^j$. Also with the rather low number of RCS per feeder this quasi exponential increase of possible configurations, might be far too much to be evaluated within several minutes. This is solved by considering not all cycles of $SC$ at once but by evolvingly increase the search space. For this the set of considered cycles $CC$ is introduced. How this is constructed is described in the following paragraph, after the elimination of the faulty *elementCell*.

### Elimination of Faulty *elementCell*

The faulty *elementCell*, represented through $e_{\text{fc}}$ is still part of $G_{\text{r}}$. But this *elementCell* must be isolated. So the first step after the cycles of the graph are found, is to eliminate it. The resulting graph is checked for its connectivity. If $G_{\text{r}} - e_{\text{fc}}$ is no longer connected, in other words, if $e_{\text{fc}}$ is a *bridge* and $G_{\text{r}} - e_{\text{fc}}$ contains two so called *connected components* the reconfiguration can not resupply all loads. Then this connected component is removed from $G_{\text{r}}$ but stored for the evaluation of the fitness function to calculate the unsupplied loads, as it is described in Section 10.3.4.

If $e_{\text{fc}}$ is only part of one *elementCell* no further actions have to be taken and the process continues with the following paragraph. If $e_{\text{fc}}$ is part of several cycles, these cycles are collected in the faulty cycle set $FC$. In the example of Fig. 10.6 the edge that represents the faulty *elementCell* $e_{\text{fc}}$ is marked with a red cross. $FC$ would contain $C^3$ and $C^4$. After the deletion of $e_{\text{fc}}$ in all the cycles of $FC$, all remaining $e \in FC$ are used to construct the faulty cycle graph $G_{\text{FC}}\left(X_{\text{FC}}, E_{\text{FC}}\right)$. On $G_{\text{FC}}$ a cycle search is performed and possible new cycles that result from the fragment cycles of $FC$ after the deletion of $e_{\text{fc}}$ are the first cycles that are added to $CC$. In Fig. 10.6 the resulting cycle after the deletion of $e_{\text{fc}}$ is visualised in red.

### Construction of Considered Cycle set $CC$

The core idea to evolvingly construct $CC$ is that not all the cycles are considered at once but that the process starts by considering only the cycles directly around $e_{\text{fc}}$. To be able to identify them is the reason why $e_{\text{fc}}$ is only deleted after the cycle search is performed not the other way round. The longer the algorithm runs, the more cycles are considered until either $CC$ contains all elements of $SC$ or the allowed time is expired. This iterative enlarging of the investigated grid area has several major advantages: Power systems are no random graphs, if the grid is planned in an intelligent way, often some designated securing lines are available in the proximity of a faulty *elementCell*. Also changes in the power flow that result from the bypassing of branches will be maximal around the faulty *elementCell*. As there might not be the time to investigate all possible solutions, this allows the concentration on the directly affected grid area. Another advantage is that a grid may contain cycles that are completely detached from the area where the fault appeared. By using $CC$ instead of $SC$, these cycles are omitted, leaving the grid unchanged in this area.

In the first iteration, $CC_1$ contains only (if available) the cycles that result from the faulty cycle set $FC$. Additionally, it includes the cycles that share an edge with $FC$. This is visualised in Fig. 10.7. The next iteration enlarges the considered grid area by including further cycles

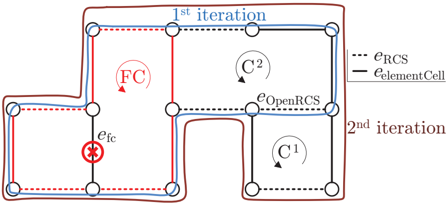



Figure 10.7: Example of the evolving construction of $CC$.

that share an edge with the previous considered cycle list. For the cycles that are part of $SC$ but not of $CC_n$ the prevailing grid configuration is kept. RCS that are open stay open, RCS that are closed stay closed. This approach is straightforward, except for one special configuration: $e_{\mathrm{RCS}}$ that are normally open and that lie on more than one cycle, but where in the actual iteration $n$ only one of them is part of $CC_n$. To avoid any remaining cycles, these $e_{\mathrm{RCS}}$ must be always open. As soon as the other cycles are also part of $CC_{n+1}$ (this happens in the next iteration $n+1$) this rule can be dropped, as the cycles are treated correctly. This is also visualised in Fig. 10.7 where $e_{\mathrm{OpenRCS}}$ is part of the cycles $C^1$ and $C^2$. As this RCS is normally open, it must be assumed to be always open in the first iteration (in blue), otherwise $C^1$ might prevail in the new configuration. This happens if instead of $e_{\mathrm{OpenRCS}}$ another $e_{\mathrm{RCS}}$ of $C^2$ is opened.

#### Generation of New Grid Configurations

Based on $CC$ an exhaustive search is performed, establishing all possible configurations $C_{\mathrm{G}_i}$ by opening one RCS of each cycle of $CC$ to generate a candidate spanning tree. The opening of a RCS is done by considering its edge $e_{\mathrm{RCS}}$ to be a chord and by removing it from the grid graph $G_{\mathrm{r}}$. Some of these open switch combinations might result in undesired configurations, e.g. isolated nodes. So every new configuration is checked if the resulting graph is connected. If this is not true, the configuration is omitted.

### 10.3.4 Evaluation of New Grid Configurations

Each new configuration $C_{\mathrm{G}_i}$ that results from the previous step, must be evaluated with regard to its electrical behaviour. This requires the solving of the power flow problem. From a runtime perspective this is the most time consuming aspect. After that, an aggregated fitness function similar to the one introduced in Section 9.1.4 is evaluated for each solution. This fitness function must be designed in a way that it rewards desired behaviour (e.g. good voltage profile) and penalises undesired properties (e.g. exceeding of admissible line currents). It also must aggregate the constraints and objectives in a way that the resulting number is significant to identify the desired behaviour of the solution. The fitness function developed for the evaluation of new grid configurations contains the following terms:

$$f = f_V + f_I + f_{\text{unsuppliedLoads}} + f_{\text{switchActions}} + \{f_{\text{SCC}}\} \tag{10.4}$$

with $f_V$ and $f_I$ the constraints that penalise inadmissible voltage deviations and exceeding currents respectively. To discriminate solutions that can not resupply all loads (outside the faulty *elementCell*), the term $f_{\text{unsuppliedLoads}}$ is introduced. $f_{\text{switchActions}}$ favours solutions that minimise the switches to be activated. $f_{\text{SCC}}$ guarantees that the thresholds of admissible short circuit currents for the protection are still respected in the new configuration. This term is placed in parenthesis. Its evaluation is the most time consuming of all the terms. So it is only evaluated when a possible new best solution is found.

For the normalisation of the terms, Eq. (9.4) is also used. The calculation of the upper limit for $f_{\text{unsuppliedLoads}}$, $f_{\text{switchActions}}$, and $f_{\text{SCC}}$ are also defined. In the following the terms of the fitness function are described more in detail.

### Power Flow Constraints

$f_V$ and $f_I$ depend on the result of the power flow and characterise the electrical behaviour of the solution. The two parameters are derived according to Eq. (9.5) to Eq. (9.7) in Section 9.1.4

### Unsupplied Loads

The parameter $f_{\text{unsuppliedLoads}}$ sums up the squares of the active power of all unsupplied loads $n_{\text{unsupplied}}$ in the grid after the removal of $e_{\text{fc}}$. This contribution to the fitness function is constant for one $e_{\text{fc}}$ in one given grid topology but can change between *intra-* and *extra-reconfiguration*

$$f_{\text{unsuppliedLoads}} = \frac{1}{n} \cdot c_{\text{unsuppliedLoads}} \cdot \sum_{i}^{n_{\text{unsupplied}}} P_i^2. \tag{10.5}$$

In this equation the coefficient $c_{\text{unsuppliedLoads}}$ is chosen to be constant and fixed to 1. It is written explicitly to preserve the coherent structure between the contributions to the fitness function. Again, the squaring of summands, as it can be seen also for the other terms of the fitness function, leads to a fitness function that is a combination of convex terms. The term is divided by the number of buses $n$ in the grid to make it a figure independent from the grid size.

### Number of Activated Switches

$f_{\text{switchActions}}$ considers the number of switches that change their position $sw_{\text{action}}$ in the new configuration with regard to the original grid configuration

$$f_{\text{switchActions}} = \frac{1}{n} \cdot c_{\text{switchActions}} \cdot sw_{\text{action}}^2. \tag{10.6}$$

$c_{\text{switchActions}}$ is again chosen to be constant and fixed to the numeric value of 1. There are several reasons to try to minimise the switching actions. One is that the activation of switches wears them out, they are sold with a certain number of switching operations. Thus, the life cycle of the devices can be improved. Also the more switches have to be operated, the longer it takes to realise a new configuration. And a third reason is related to the heuristic nature of the algorithm: Trying to reduce the number of switching operations works as an equaliser to promote simple and clear solutions that are as close to the original grid configuration as possible.

### Short Circuit Currents

A new grid configuration must still respect the protection specifications at the feeders. To guarantee the correct function of the protection, the smallest possible fault current at a node connected to a feeder $I^{\mathrm{node}}_{\mathrm{sc}_{\min}}$ must still be above the limits given by the protection device on this feeder $I^{\mathrm{feeder}}_{\mathrm{sc}_{\min}}$ as described in [177] This is verified by assuming a phase-to-phase fault on different places in the grid. The short circuit current $I^{\mathrm{node}}_{\mathrm{sc}_{\min}}$ in this case is

$$I^{\mathrm{node}}_{\mathrm{sc}_{\min}} = \frac{V_{\min}}{2 \cdot Z_{\mathrm{sc}}} \tag{10.7}$$

with $V_{\min} = c_{\min} \cdot V_{\mathrm{ref}}$ and $Z_{\mathrm{sc}}$ the impedance seen by the short circuit. The calculation is done following the norm IEC 60909 and by using the method of equivalent voltage sources [39, p. 819-866]. This norm defines the minimal voltage factor for the medium voltage grid with $c_{\min} = 1$. The short circuit is calculated for all nodes in the grid that have only one neighbour, thus the ends of the laterals. This is done by using the inverse of the nodal admittance matrix $Y$ [128]. The approach of equivalent voltage sources also allows the inclusion of the contribution to the fault current from possible distributed generators in the grid. This term is only evaluated for a possible new best solutions. Should at one feeder in the grid an $I^{\mathrm{node}}_{\mathrm{sc}_{\min}}$ be smaller as the threshold of the protection $I^{\mathrm{feeder}}_{\mathrm{sc}_{\min}}$ a very high value is added to the fitness function that leads to an exclusion of the solution.

One could imagine an additional parameter with regard to the high voltage source of the substations. High equalizing currents can occur when load is transferred from one primary substation to another if the two substations are not fed by the same high voltage source. But normally this is already taken into account in the construction of the grid, not allowing the connection of different distribution grids.

### Calculation of $f_{\mathbf{X},\mathbf{Max}}$

To be able to normalise the terms of the fitness function, an approximate upper limit must be calculated. The calculation of $f_{V,\max}$ and $f_{I,\max}$ is described in Eq. (9.12) and Eq. (9.13) respectively in Section 9.1.4. The calculation of $f_{\mathrm{unsuppliedLoads,max}}$ and $f_{\mathrm{switchActions,max}}$ is described in the following. The term $f_{\mathrm{SCC}}$ does not need to be normalised because as soon as $f_{\mathrm{SCC}}$ is non zero, the solution is never chosen as possible best solution.

$f_{\mathbf{unsuppliedLoads,max}}$ To calculate the upper limit, it is assumed that any load of the grid can be supplied and $f_{\mathrm{unsuppliedLoads,max}}$ is calculated by summing up the squares of all loads $P_i$ connected to the grid

$$f_{\mathrm{unsuppliedLoads,max}} = \frac{1}{n} \cdot c_{\mathrm{unsuppliedLoads}} \cdot \sum_{i=1}^{l} P_i^2, \tag{10.8}$$

with $l$ the number of loads in the grid. Again this value is divided by the number of buses in the grid $n$ to create a relative number.

$f_{\mathbf{switchActions,max}}$ The upper limit for switching actions is derived by assuming that every RCS in the considered grid area changes its position, i.g. all open switches are closed and all closed switches are opened. The upper limit is thus the square of the number of RCS $n_{\mathrm{RCS}}$ available in the grid

$$f_{\mathrm{switchActions,max}} = \frac{1}{n} \cdot c_{\mathrm{switchActions}} \cdot n_{\mathrm{RCS}}^2. \tag{10.9}$$

### 10.3.5 Self-Healing with Flexibility Use

If the evaluation of the fitness function of a possible new solutions shows minor problems with regard to the power flow constraints $f_V$ or $f_I$, flexibilities that are provided by *prosumers* can be use to eliminate or reduce them. This is especially interesting for e.g. high load situations, where without flexibilities voltage and/or current constraints would be violated with a new grid configuration. Flexibilities can help to bring the grid parameters back into an admissible range. The optimal choice of flexibilities is done with a heuristic particle swarm approach (PSO) that is introduced in Section 9.1.

## 10.4 Validation through Simulation

The above described approach was implemented as described in Appendix D.3.5. It was then validated on two different test grids. The first one is the 70 node distribution grid introduced in [162] and further described in Appendix A.3. Further on, the approach was validated on real grid data from a fraction of a French distribution grid, see Appendix A.4 for further information about this grid.

### 10.4.1 Validation on 70 Node Grid

The 70 node test grid was the basis for the first two test cases. Its structure is given in Fig. 10.8.

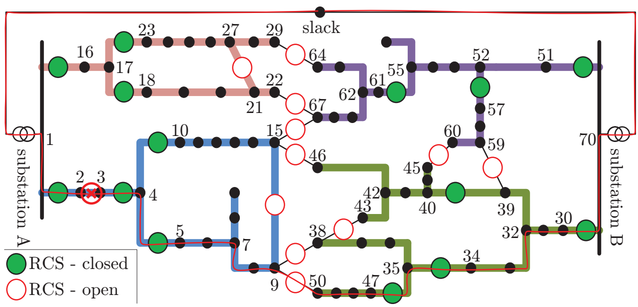



Figure 10.8: Test grid taken from [162] inclusive added RCS.

#### Test Case 1: Original System

The first test case to be validated was a fault between node 2 and node 3 in the grid area of substation A. This resulted in an open circuit breaker between node 1 and node 2, leaving the blue feeder unsupplied. The fault identification found as faulty *elementCell* the grid segment between the circuit breaker (1-2) and the RCS 3-4. A test showed that the *inter-reconfiguration* could not be used as the inclusion of the two inter-reconfiguration open switches (RCS 9-15 and RCS 21-27) of substation A does not result in a cycle that includes the faulty *elementCell*. But by relying on the securing substation (substation B) and the extra-reconfiguration open switches that combine the two *substation federations*, it is possible to find new configurations as it is visualised exemplified with one cycle in red on Fig. 10.8. The final best solution was to isolate the *elementCell* by opening the RCS 3-4. Then the two extra-reconfiguration open switches RCS 9-38 and RCS 15-46 were closed. Further on, to eliminate the resulting cycle, RCS 4-5 was opened. In total 21 576 solutions were evaluated. On a laptop with a CPU of 4 processors from type Intel Core i7-3520M with 2.9 GHz this took less than 50 seconds. The final grid configuration is shown in Fig. 10.9. However, for this grid no information about the

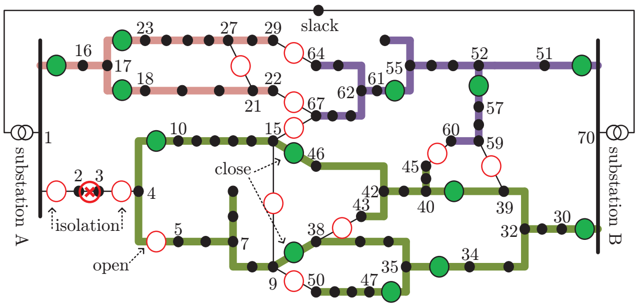



Figure 10.9: New grid configuration for a fault in *elementCell* 2-3.

protection devices was given. So the evaluation of this term was omitted. From the number of nodes, this validation grid is rather a small grid. However, from the point of combinatorial possibilities, it is rather a large grid as it contains 21 RCS, roughly 5 RCS per feeder (exclusive the circuit breakers). As already highlighted, the average in France is about 2 RCS per feeder [101]. This explains the large number of possible solutions.

### Test Case 2: Current Constraints

The maximal admissible current of the feeder behind the circuit breaker 30-70 of substation B is 270 A. Before the reconfiguration this current is around 89 A and after around 144 A. In a second test case the maximal admissible current on this branch of the grid is reduced to 120 A, making the above present solution invalid. Assuming the initial configuration of Fig. 10.8 the self-healing with this modified data set results in the following new grid configuration: The faulty *elementCell* is again isolated by opening the RCS 3-4. Further on, the switches RCS 45-60, RCS 9-38, RCS 15-46 and RCS 22-67 are closed and the switches RCS 55-61, RCS 39-40 and RCS 4-10 are opened, see Fig. 10.10 In this configuration the current on the respective branch is around 93 A. This solution requires more switching actions than the previous solution. However, one could imagine situations where the reconfiguration can not find a valid solutions. But if the grid respects the n-1 security, generally the here presented approach will find a valid new configuration.

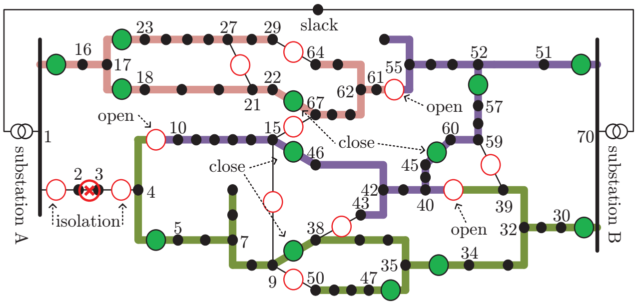



Figure 10.10: Alternative configuration with reduced admissible current through feeder 30-70

## 10.4.2 Validation on Real Grid Data

Further on, the approach was validated on real grid data from a fraction of a French distribution grid, see Appendix A.4 for further information about this grid. This grid later hosted the field test. This allowed a direct comparison and prediction of how the system would react. The following pictures, Fig. 10.11 - Fig. 10.15 contain all the RCS - named IPT - that are available in this grid, in green those that are closed, and in red those that are open. The circuit breakers at the feeders, are also visualised. The grid area contains five medium voltage *prosumers* that are visualised with a generator sign, and that will play a role when it comes to the use of flexibility in the second test case of this section.

#### Test Case 1: Extra-Reconfiguration

To trigger the reconfiguration approach in simulation, the affected *substation DSO* receives roughly the same information, the operator would receive at the control centre who then would manually solve the problem. For the here presented test case, `ALTE_DJ25` trips following a permanent fault, disconnecting the whole feeder and the FPIs at `IPT179` and `IPT177` are activated. The first step for the *substation DSO* at *Altenstadt* is to identify the faulty cell, it lies for the here described case between `IPT177` and `IPT6063` as shows Fig. 10.11. After that, the possibility to find a new configuration within the *substation federation* is checked. But as there are no "intra-substation open switches" that would resupply the part of the feeder behind the faulty cell, this step is skipped and the *extra-reconfiguration* is started. The first securing partner of *Altenstadt* is *Lauterbourg*. The *substation DSO* at *Lauterbourg* provides the necessary information and the *substation DSO* at *Altenstadt* can run the self-healing method. For this test case 192 solutions were evaluated. This took less than 17 seconds. The proposed solution is to first isolate the faulty cell, this is done by opening `IPT177` and `IPT6063`. Then the circuit breaker `ALTE_DJ25` can be reclosed. To resupply the rest of the feeder, the `IPT6014` is closed, so this part is now fed by the substation of *Lauterbourg*, see Fig. 10.12 for the solution. In this test case also the short circuit behaviour is tested, as for this grid all the required data was given. There might exist other, maybe even better solutions for example to resupply via the `IPT6062` of the *substation DSO* of *Roeschwoog*. But as the *substation DSO* of *Lauterbourg* is in the list of securing substations above the one from *Roeschwoog*, this solutions is evaluated at first. And as it is a "good" solution, there is no need to try further solutions.

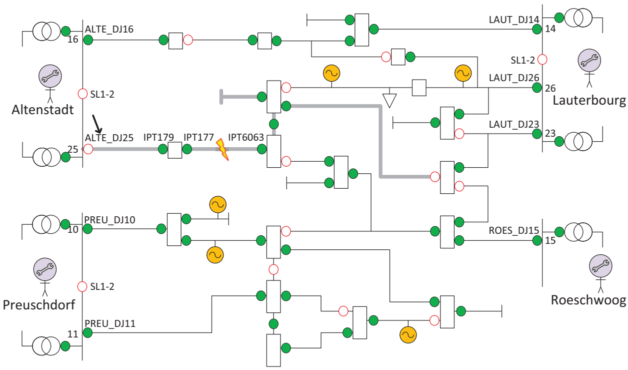



Figure 10.11: Fault between `IPT177` and `IPT6063` of *Altenstadt* leaves the whole feeder unsupplied.

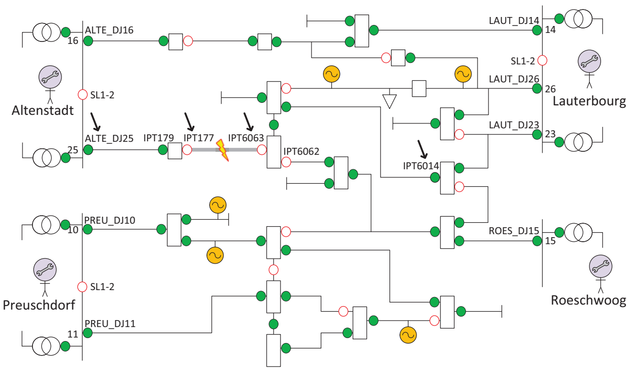



Figure 10.12: Resupply via `IPT6014` reduces the unsupplied area.

### Test Case 2: Intra-Reconfiguration with Flexibility Use

The second test case was triggered by the tripping of the circuit breaker `PREU_DJ10` and the activation of the FPIs at `IPT976`, `IPT975`, `IPT161` and `IPT160`, see Fig. 10.13. The process of identification the faulty cell localised the fault between `IPT160` and `IPT6041`. The resupply is possible by the *intra-reconfiguration*, but as the grid is rather heavy loaded at this period, the solution relying on the closing of `IPT6040`, would result in a violation of the voltage profile for the grid section behind `IPT6042`, see Fig. 10.14 the green plus signs. So the solution is optimised by the use of flexibilities, provided by *prosumerB* to *prosumerD*, as described in Section 10.3.5. All three *prosumers* propose active as well as reactive power flexibilities to the *substation DSO*. The voltage profile violation is best solved with reactive power injection from the *prosumerD* as the other two prosumers are on the other feeder and their behaviour does not influence the affected parts. The final solution is visualised in Fig. 10.15, the faulty cell is isolated by opening `IPT160` and `IPT6041`, the circuit breaker `PREU_DJ10` is closed again and the resupply of the grid parts behind the faulty cell is realised with `IPT6040`. The drawback

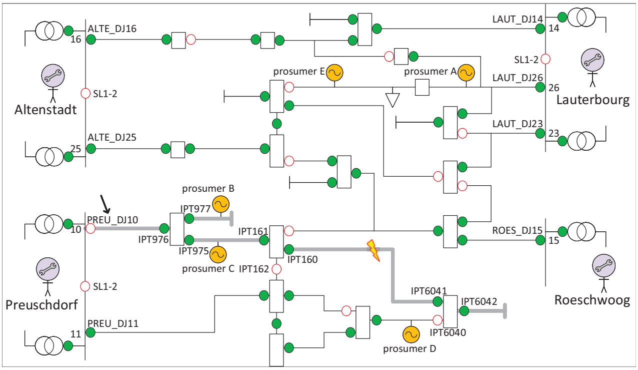



Figure 10.13: Fault between `IPT160` and `IPT6041` leaves the whole feeder of *Preuschdorf* unsupplied.

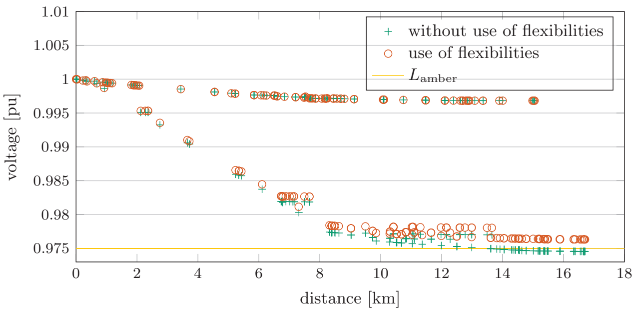



Figure 10.14: Voltage profile of affected grid area without (green plus signs) and with use of flexibility (orange circles).

of the inclusion of flexibilities is that the calculation time exceeds the three minutes as the reconfiguration is combined with the flexibility optimisation.

### 10.4.3 Comparison with Existing Approaches

The reconfiguration used for the optimisation of the grid state has as major objective the reduction of power losses. The main objective of the reconfiguration for service restoration is to supply as many loads as possible, while respecting operational constrains like the voltage profile. Further on, the solution should be available as fast as possible and the number of activated switches should be as low as possible. As communication is often a bottle neck, the number of messages that need to be exchanged is also a performance criteria, especially in the context of distributed systems. The approach proposed in this thesis is compared against two acknowledged methods, a decentralised and a centralised approach. The approach presented in this thesis finds in both cases the same solution as in the original papers. Thus instead of metrics like losses or the voltage profile, the comparison is done based on internal characteristics of the approaches.

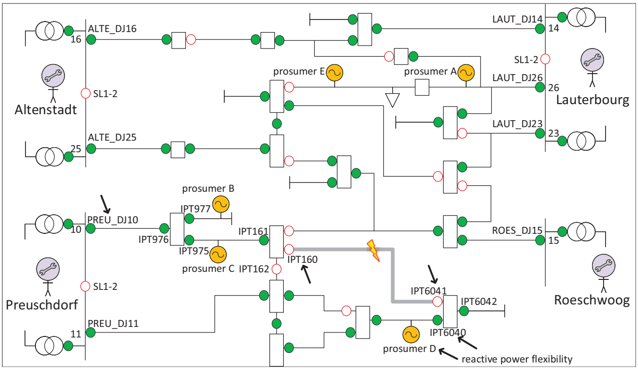



Figure 10.15: Resupply via `IPT6040` and the use of reactive power flexibilities of *prosumerD*.

### Decentralised Approach

The first comparison is against the fully decentralised approach presented in [169]. The test case 1 of [169] is also considered with the approach developed in this thesis. For this, all switches of the test distribution network are assumed to be RCS. There exist two *substation DSOs*, one for each source. Table 10.1 gives a comparison of major characteristics. Both approaches

Table 10.1: Comparison of major characteristics between proposed and fully decentralised approach.

| | Proposed approach | Fully decentralised approach [169] |
|---|---|---|
| Agents | 2 | 39 |
| Messages | 5 | 67 |
| Power flow calculations | 1 | 0 |

find the same solution. But while the approach in [169] requires an exchange of 67 messages, only 5 messages need to be exchanged in the here proposed approach: one to request the *extra-reconfiguration* with the securing source, one to confirm the *extra-reconfiguration*, one to inform the securing substation about the new configuration, one message to open S11, and one to close S34. Also the reduced number of agents (2 instead of 39) is an important aspect with regard to practicality.

### Centralised Approach

The second comparison is against the centralised approach presented in [178]. This centralised approach relies on a mixed integer linear programming approach that obtains the switching actions necessary for the resupply. For this it requires between 13 and 14 seconds. The 44-node test system presented in [178] has also been tested with the proposed approach of this thesis. All switches that are given in the test system are considered to be RCS. The total execution for this test case took around 4 seconds. It finds the same solution for the configuration as the original paper for case 1. In the work of [178] the minor voltage profile violations that persist in this configuration are mitigated by load shedding actions. This can also be realised by including the use of flexibilities as described in Section 10.3.5 into the self-healing approach.

Therefore, the approach presented in this thesis is a promising compromise between a centralised and a fully decentralised approach.

## 10.5 Conclusion

The proposed method for the reconfiguration of the radial distribution grid is mainly developed for the fast identification of possibilities to resupply as many loads as possible after a permanent fault led to the outage of a feeder. Its basic concept relies on distributed control devices that are part of advanced substation automation. It does not does not solve the problem globally but as locally as possible, thus reducing the search space. Mathematically, a spanning-tree problem is solved, where the considered graph is enlarged progressively. To evaluate new configurations, their fitness function needs to be calculated based on multiple parameters. This fitness function evaluates the electrical behaviour. For grid situations in which reconfiguration alone reaches its limits, the approach can be combined with the use of flexibilities.

Validated in simulation on test grids and real grid data the here proposed self-healing helps to decrease the outage time for the customers. It also reduces possible fees, the DSO has to pay to the regulator. Further on, the comparison with other types of self-healing approaches shows that it has advantages with regard to practical parameters. The approach relies on RCSs that generally are rather sparsely available. This is a unique feature of the here proposed method and together with the specialised algorithm the reason why the approach is able to solve the problem in near real time after the fault. The here presented approach, as well as every other approach for the self-healing of the grid that bases on the reconfiguration, reaches its limits for grids that are operated at their capacity limit and that do not possess any n-1 security. The more the grid is utilised, the more complex the problem gets.

As the new grid configuration is calculated after the fault this method relies on the actual grid state. Thus, the presence of distributed generators in the grid is taken into account. Further on, flexibilities of these generators can be used to support the grid in degraded operation.

The application as part of a field test at a French DSO (see Appendix E.3.2) completes the validation of this method and shows its feasibility as an addition to classic IEDs in the substation.

CHAPTER 11

# Counter Measures against Cyber Threats

In previous chapters of this thesis three major resilience enhancing aspects and functions have already been introduced:

- the distributed-hierarchical operation architecture, see Section 7.2,
- the combination of optimisation and local control, see Section 7.5.3,
- and the automated self-healing method, see Chapter 10.

This chapter considers additional aspects and functions that increase the resilience against threats that arise from the increasing dependency of the power system operation on the ICT infrastructure. These functions focus on the absorption resilience capabilities as introduced in Section 2.2.3.

Such cyber-related threats are rather new but alarming and at the same time generally not in the focus of an electrical engineer. A list of reported attacks on the power system can be found in [13, p. 6f]. And the authors of [14] list cyber-related outages of the power system resulting both from errors and attacks. Such attacks could be realised as denial of service attacks, malware, intrusions, routing attack and protocol-based attacks [13, p. 7]. The author of [179] gives a list of SCADA threats related to the IT components. These threats are not exclusively related to attacks but also related to non-intentional or negligent misbehaviour.

It is important to say that the IT development has not been idle against this rising danger. Advanced solutions to secure IT systems of the power system infrastructure have and are being designed. This includes physical access control, scanners and intrusion detection systems to detect malware, firewalls and encryption techniques like the public key approach, as well as hash-based process filtering [180]–[183]. All these concepts fall into the category "protection" as introduced in Section 2.2.2. And it would be too optimistic to rely only on the protection, especially for such an essential infrastructure as the power system. Resilience enhancing counter measures are required that minimise the negative effects in the case that the protection is not sufficient.

The introduction of this thesis already gives a list of possible threats that arise from the digitalisation of the power system. The following section systemises the main threats. Also several resilience enhancing aspects of the grid operation developed in this work are mentioned. Section 11.2 proposes a list of further counter measures specialised on disturbances and attacks resulting from the dependency between power system and ICT. Parts of the work described in this chapter have been previously published in [D6].

## 11.1 Threats Resulting from Dependency on ICT Infrastructure

Possible threats resulting from the interdependency of the ICT infrastructure and the power system can be systemised by assuming that a smart grid is in its core similar to any complex computer system [13, p. 7]. In correspondence with the classic information security triad confidentiality, integrity and availability, the same security objectives apply to smart grids. Confidentiality protects confidential data and information and prevents its unauthorised dissemination. Integrity prevents the unauthorised and undocumented modification or insertion of data and information. Availability guarantees that devices in the IT infrastructure are up and respond with the requested data or behaviour within a given time frame. In smart grids these security objectives apply in a reversed priority (availability, integrity, confidentiality) as availability is the most important objective to guarantee, followed by the two others [184], [185].

All possible cyber attacks on smart grid infrastructure can be mapped as an attack on one (or a combination of) security objectives [185]:

- **On availability**: mostly denial of service (DoS) attacks. One or more resources are deliberately made unreachable by communication methods. This is mostly done by flooding the communication network or a particular device with corrupted packages so that the designated information can no longer be transmitted.
- **On integrity**: bad data injection. The data exchanged between resources is altered or injected so that a desired behaviour of the devices can be induced or that wrong decisions are made by the control units.
- **On confidentiality**: Sensible and confidential data and information is captured.

This list can be enlarged to include attacks on further security objectives like non-repudiation, authentication, and authorisation. This leads to the so called STRIDE threat categorisation that is widely used in software development [186, p. 160-164] and that is the basis for the disturbance identification during the resilience evaluation in Chapter 6. But the smart grid is not only a complex computer system. As described in Section 4.3.2 it builds a cyber-physical system with the ICT devices and the hardware components of the power system. Therefore a forth type of cyber attack is somehow related to the three types named above, but with the target not to disturb the ICT part but to target the physical device for example the primary substation, the generator, etc. [187]. As the replacing and repairing of components in the power system can take several weeks up to several month, this is a way to achieve long-term outages.

In the context of the power system, an attack on the availability (communication disruption) can take two forms. Either the server required for the communication is targeted, resulting in a complete loss of communication. Or - especially if the communication does not require any server - specific actors are made unresponsive. An attack on integrity and the injection of false data can include the tampering of measurement data and status information or the faking of control signals.

These threats can origin from various sources. In [188, p. 16ff] a list of possible threat sources is given ranging from criminal attackers (like terrorists or economic criminals) to natural hazards or accidents. For simplification, this thesis assumes that the threat tends to result in the most severe consequences. The most severe consequence in the power system is a long-lasting, wide-area breakdown. That means an attack targeting the confidentiality itself is not (yet) a danger for the grid stability. The captured data can be reused to launch further attacks, but in itself it does not put the operation at danger. As this thesis investigates strategies to strengthen the grid operation, this type of attack is not considered here.

A system that is resilient against the above mentioned attacks, is also able to withstand technical failures:

- An attack on the availability is comparable to a situation where a communication device breaks down or the communication is interrupted for any technical reason.
- An attack on the integrity is comparable to a situation where a sensor is not working correctly and is sending false data or a device is wrongly programmed.

Thus, in the following not the attacks themselves are considered but the resulting effects on the grid that could also emerge from technical failures. That means that possible counter measures can not only be applied as answers against cyber attacks but more generally as fall back strategies for failures of grid components.

An additional threat that is not (necessarily) related to the ICT infrastructure is the outage of the upstream high voltage grid or of parts of the distribution grid. But for the sake of completeness, it is still considered in this chapter. The first column of Table 11.1 summarises the threats described above.

## 11.2 Counter Measures

Against the threats introduced in the previous section, this section describes a set of counter measures considered for the work of this thesis. These counter measures are not intended as measures to increase the protection. They do not prevent the threats. But they are intended to increase the resilience of the system so that the effect of a disturbances is reduced. Table 11.1 summarises the threats and the counter measures considered in this work. It also describes which type of resilience capability, as introduced in Section 2.2.3, is increased by the proposed counter measure.

Table 11.1: Collection of threats and the proposed counter measures.

| Threat | Counter measure | Resilience capability of counter measure |
|---|---|---|
| **Outage** | | |
| Outage of upstream high voltage grid | Islanding (Section 11.2.4) | Adaptive and operation restoration capability |
| Outage of part of distribution grid | Self-healing (Chapter 10) | Adaptive and operation restoration capability |
| **Communication disruption** | | |
| Disruption of communication server | Local control (Section 9.2) and distributed communication servers (Section 11.2.1) | Adaptive and absorptive capability |
| Disruption of specific actor | Distributed architecture (Section 7.2) and adjusting of control mode (Section 7.5.3) | Absorptive and adaptive capability |
| **False data** | | |
| False control signals | Validation of control signals against local measurements (Section 11.2.3) | Absorptive capability |
| False measurements | Bad data detection (Section 11.2.2) | Absorptive capability |

### 11.2.1 Suitable Communication Infrastructure

The design of the communication infrastructure has a high influence on the possibility to operate the system in degraded situations. This applies to the three aspects of communication as introduced in Section 5.2.3: the information flow, the service layer and the technology. One design principle for resilient communication is that the dependency on external resources should be minimised. In Ethernet based systems, the power supply of routers can be such an external resources as well as the name (DNS) and configuration (DHCP) servers. If one of the latter two is required, the outage of one of them can hamper the communication. These examples affect the resilience of the technology aspect of communication. The choice of service layer also affects the resilience. Server based communication generally has a single point of failure from a communication point of view. An outage of this server can massively disturb the communication. But one of the most effective resilience increasing concepts is the concept of segregation, that means to separate infrastructures and minimise their dependency [26, p. 118]. If a certain information is not required, its absence does not put the system in danger. Thus the reduction of necessary information flow is a key approach to increase resilience.

In spite of its above mentioned drawback, this work assumes a server based communication method. Reasons for this choice are given in Appendix D.1.3. To attenuate the dependency on a single communication server, several independent communication entities are realised, see Fig. 11.1. The actors within a *substation federation* communicate via a so called “local communication server”. This local communication server is physically hosted in this federation and can run even if other parts of the communication infrastructure are corrupted. The “global communication server” is used to provide communication capabilities between *substation federations*, the *aggregators* and the control centre. In the event of an outage of the global communication, each *substation federation* is operated independently.

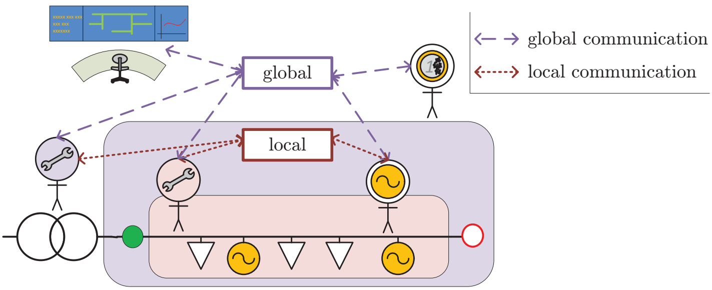



Figure 11.1: Use of global (violet) and local (dark red) communication server.

### 11.2.2 Bad Data Detection in Measurements

Approaches that allow the detection of false measurements, due to defect measurement devices, during the state estimation of the power grid, are almost as old as the state estimation for the power grid itself [189]. The authors of [105, p. 99] present some brute-force tests that allow the detection and elimination of obvious false data like negative voltage magnitudes, several order of magnitudes difference between the measurement and the expected value and large inequalities between the incoming and the outgoing currents of a node (Kirchhoff’s law). More advanced methods for the detection of so called “bad data” classically rely on the use of $\chi^2$-distributions or the use of normalised residuals [190], [105, p. 105-115]. The latter one can also be used to identify the bad measurement and not only state its presence. As the detection of false data with $\chi^2$-distributions fails rather easily as the normalised distribution of errors is required, the normalised residuals approach is the default method in this work.

These classic methods can only be used to identify bad data in measurements whose elimination would not make the system unobservable. Basically, these approaches can also be used to detect deliberately forged measurements, but only to a certain extent [191]. If the attack is very sophisticated, and the attacker can rely on inside information about the grid topology, attacks can be designed that can not be detected by the approaches mentioned above [192].

### 11.2.3 Validation of Control Signals against Local Measurements

One of the major concerns with regard to cyber attacks is that the attacker might get access to the control infrastructure and injects its own tampered control signals. This would fall into the category of false data attacks as described in the previous section. A special danger of these attacks lies in large scale coordinated attacks that could create fast and sudden load or generation losses. This has the potential to destroy the precious frequency balance of interconnected systems and can result in massive blackouts. This problem is especially considered together with the widespread introduction of smart meters that come with a remote on-off command [193]. But the same effect could be realised by the coordinated opening of switches to separate larger parts of the grid or to send a similar on-off signal not to loads but to distributed generators.

The counter measure that is proposed in this thesis is based upon the work published by Temple, Chen and Tippenhauer in [194]. In their work, they present an approach where the negative effects of remote smart meter disconnection attacks is mitigated by a random time delay that is introduced by the smart meter between the receiving of an on or off command and its actual execution. In the above cited article the optimal time delay lies within two hours. This leaves time for the utility to find out that there is a problem.

These two hours are fare too long, if one considers a similar application for switching signals or generator shedding. But to mitigate the effects of such instantaneous changes on the grid stability a smaller time slot might be sufficient. Primary control reserves are available within several seconds, secondary control reserves at the latest within minutes [195]. To give them a chance to react to the disturbances created by coordinated on or off signals, the execution of actions is delayed randomly within the time slot of 30 seconds to one minute. This delay time is in line with what is generally assumed as reaction time, if the switching signal is issued by human intervention in the control centre.

The interconnected European power system is designed to provide up to ±3000 MW of primary control reserve within 30 s [195]. The secondary control reserves for Germany lie around additional ±2000 MW [196]. With loads around 40 GW to 80 GW in Germany [39, p. 35] this covers attacks that target around 10 % of the overall load.

For a lot of cases this delay of half a minute up to one minute is acceptable, for example if a line needs to be isolated because of maintenance work. But there might be cases when even this delay is too long and near real-time reactions on the control signals are required. Naturally, the automatic under-frequency load shedding relay is not affected by this delay. It still reacts within the time frame of 200 ms after the under-frequency has been detected. And also the opening of circuit breakers because of protection issues is naturally excluded from this time delay. Thus, the delay only applies to remote signals.

To help with the distinction between control signals that come from an authorised person or device caring for the grid stability and control signals that are possible hazardous, control signals are validated against local available measurements. Signals that "make sense" also from a local perspective of the devices are executed directly, while only those that are not reasonable from a local perspective are delayed by a random time delay. Thus the task is to define what is sensible and what not. This question is especially considered from a frequency perspective. As the frequency is everywhere the same in the interconnected systems, it gives information about the overall system state. If the frequency that is measured by the *substation DSO* is already reaching an upper limit and the *substation DSO* then receives the control signal to open the switches on its feeders, the time delay is applied, and the feeders are opened after the random delay. In another case, when the frequency is already too low, and the same signal is given, the *substation DSO* opens directly the switches. This can even be improved, as the *substation DSO* has measures that indicate if a feeder is a net load or net generation feeder (by analysing the direction of current). So it opens only those feeders immediately that are net loads, and applies the delay only to the feeders that are net generating. Same ideas can be implemented for distributed generators or controllable loads.

### Example

The above described concept has been exemplarily tested for its feasibility on an example system. This system, as well as the behaviour of the primary and secondary control are implemented according to the parameter given by [197, p. 217]. For the simulation, the so called "Mittelzeitmodell" is used based on an implementation of Dirk Fetzer, University of Kassel [198]. The system consists of two generators that are equipped with primary and secondary control reserves as given in [197, p. 217] and an aggregated load of 1000 MW. Forced by a malicious intervention at a certain moment in time $t = 0$ s, 200 MW that represents 20 % of the overall system load, receive a disconnecting signal. This 200 MW represent 8 high to medium voltage substations. In one case, visualised in green colour in Fig. 11.2, this separation happens more ore less instantaneous and all eight substations are disconnected at once. In the other case - see the orange line in Fig. 11.2 - although the disconnecting signal reaches all substations roughly at the same time, the switches in the substation open randomly after a certain time delay within 35 s.

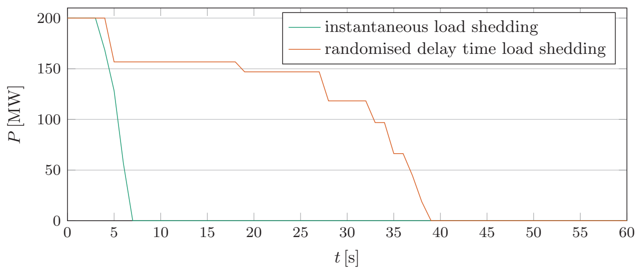



Figure 11.2: Load shedding either instantaneously (green) or with random time delay (orange).

The effect of these two types of load disconnecting on the system frequency is visualised in Fig. 11.3. Again the green curve gives the frequency deviation following the simultaneous disconnection. Mainly in the seconds directly following the disconnection high deviations from the base frequency can be observed. This can destabilise the power system and might result in outages especially if such a "switch off" signal is directly followed by a "switch on" signal. Generally any frequency deviation larger than $\pm 200$ mHz should be avoided.

In the other case - see the orange line in Fig. 11.3 - the load shedding after randomised delay time, the changes in the load can be absorbed by the primary and secondary control of the two generators. This leads to variations of the frequency that stay within the bandwidth of ±200 mHz. As the time constants of this delay are much larger than the time constant of

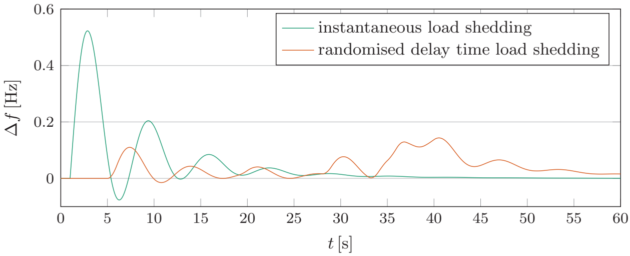



Figure 11.3: Frequency oscillations following the load shedding.

the automatic under-frequency load shedding, no negative influences, especially oscillations, on the latter are expected by the random delay.

### 11.2.4 Islanding

The increasing penetration of distributed energy resources into the low and medium voltage grid and the growing possibility of ICT provide new ways of operating the power system. This has already been addressed in Section 2.1 in the introduction. In the approach, which is often revered to as **microgrid**, rather small parts of the grid build up a unit with its own controller that operates and optimises the grid cell, taking the available resources into account [199], [200]. This approach is also the basis for the grid operation presented in this work.

But further on, the microgrid approach allows another form of operation: The microgrid can be separated from the upstream grid, for example after an outage on the upstream grid, and be operated independently without physical connection to the other parts of the grid. In this case, the microgrid transits to an islanded mode of operation [200]. All loads of the microgrid must be supplied by generators that are also part of the microgrid. The main challenge for this kind of operation is the frequency and the voltage stability, which becomes increasingly difficult with decreasing grid size [199], [201].

To solve this, the first approach is to use droop-control for all distributed generators (reactive power to control the voltage, active power to control the frequency) [199]. But these approaches reach their limits when it comes to non-linear loads, and can lead to considerable variations in the voltage and frequency according to the load [201]. Thus, approaches have been developed that take the transmission grid as an example and use central controllers within the microgrid area doing secondary control [201], [202].

In the work of this thesis, distributed controllers are already used for the standard operation. The islanded operation is considered to be an extension and supplementary operation mode that can be used to bridge interruptions of the upstream grid. It is thus generally acknowledged that microgrids increase the resilience of power systems [32], [203], [204]. The additional functions required for the islanded operation can be hosted in the already existing distributed controllers.

For the sake of completeness, microgrids are included in this list of counter measures, but the implementation and enhancement of a suitable microgrid controller is out of scope of this work. The development of microgrids is a research field of its own.

## 11.3 Limitations and Outlook

The above described solutions have one limitation: They require the implementation of additional functions in some programming language. But every code can have bugs that make it vulnerable for random errors or targeted attacks. So the counter measures could be manipulated or switched off. Another large problem that has not been addressed in this work is the update problem. Software generally requires updates to close vulnerabilities but especially for complex systems with lot of interactions that need to run 24/7 updates are difficult to make without weakening the system. Also in distributed systems like the here presented architecture updates can be a problem and can be misused to infiltrate the system with malware. A possible solution for these limitations is the development of formal verified code. The formal verification guarantees the behaviour as defined in the formal definition. Without any further security mechanisms this prevents classic security leaks like memory leaks, null pointer access or buffer overflow [205]. First prototypes of such code are already used [205], especially in military applications [206].

# PART IV

# VALIDATION AND CONCLUSION

CHAPTER 12

# Validation through Simulation and Realisation in Field Test

Testing and validating the new methods and functions in simulation is an important step in the course of every engineering development. Also the ideas proposed in this work have been validated in simulation, and additionally realised in a field test environment.

Simulations are mainly used to demonstrate the proof of concept. This is equivalent to the technology readiness level (TRL) 3, according to the classification of technology readiness levels by the European Commission [207]. Section 12.1 introduces the environment for the simulation based validation. However, the work of this thesis has achieved a technology readiness level up to 5 as major aspects of this work have been "validated in relevant environment" [207]. This means they have been validated in a field test and have interacted with real world devices and infrastructure. This field test is introduced in Section 12.2.

## 12.1 Validation in Simulation

The distribution grid operation and its methods are realised as comprehensive software package that is called the "distributed grid operation kit". This software package is written in the programming language Java. It implements the distributed-hierarchical operation architecture described in Chapter 7 with appropriate communication mechanisms. For the main players, the *DSO agents*, it further includes the methods and functions developed in the Chapters 8 to Chapter 11 to build a comprehensive and resilient grid operation. The other actors like the *prosumers* and *aggregators* are implemented as far as required to be able to interact with the grid operation. For the specialised context of power systems, necessary functions like the solving of power flow equations were also implemented. Further on, the software package also includes a so called *grid simulator* that behaves like the real grid if the grid operation would interact with the physical devices of the grid. Appendix D gives detailed information about the implementation of the software package.

Main objective of the simulations was to prove the concepts in a realistic but still simulated and fully controllable environment. Apart from the concept validation, the simulations paved the way for the tests in the real-world environment. Thus, the grid operation developed in this thesis was combined with the co-simulation platform OpSim [208], [209]. Further details on this integration can be found in Appendix D.4.

## 12.2 Field Test

The main objective of the field test was to demonstrate the concepts of this work in a real-world environment and validate its desired behaviour. For engineering projects this is always an important step that needs to be taken to increase the technology readiness level.

The field test of this thesis was part of the European funded FP 7 project "DREAM". It was realised together with the the French DSO *Strasbourg Électricité Réseaux* and several manufacturer partners, among others *Schneider Electric*. *Strasbourg Électricité Réseaux* is the second largest DSO in France, and operates major parts of the the electric grid in Alsace, supplying more than 400 municipalities including the city of Strasbourg. Its grid has a length of over 14000 km, containing 9000 km low voltage, 4500 km medium voltage (20 kV) and includes also more than 700 km of 63 kV and 220 kV lines, unique for a French DSO [210]. On this grid area, a dedicated field test zone has been selected, containing four high to medium voltage substations and eight feeders of these substations. Fig. E.1 in Appendix E gives the outlines of this test area.

For the field test, the operation architecture introduced in Chapter 7.2 has been realised as far as possible. This required some compromises, especially with regard to the parallel operation of the "standard" grid operation through the SCADA system and the "new distributed" operation. The distributed-hierarchical operation architecture was realised by virtual machines running on workstation PCs or servers. But also standard devices like remote terminal units (RTU), that are used to build the interface between switches and the SCADA system, were integrated into the system. For that purpose, state-of-the-art RTUs were equipped with additional functions. Further on, a PV system as well as two charging stations for electric vehicles were part of the field test, playing the role of the *prosumers*.

These components were put together to realise new functionalities. Apart from an increased visibility, the two main functionalities to be tested were the optimisation of the grid state (see Appendix E.3.1) and the self-healing (see Appendix E.3.2).

From the beginning on, the development of these new functions was strongly coordinated with the involved DSO. This was crucial for the successful testing and avoided deceptions and false expectations on both sides.

This field test is the subject of an article published by the author of this thesis in cooperation with the major contributors to the tests [D7].

## Lessons Learned in Field Test

During the field test, the control centre of the DSO was operating the classic SCADA system for its normal operations, while the new functionalities were tested in their distributed way. This configuration required sometimes creative and unconventional solutions to be implemented. Indeed this could be the starting point for most of the equipment renewals for DSOs, as it is unrealistic for them to replace all of their ageing equipment in a short time frame. Consequently it is critical to be able to maintain the ageing and newer infrastructure in perfect and parallel working conditions. During the field test, some important experiences could be gained in this field. Even though the new optimisation could not fully be exploited, mainly due to the good grid conditions, the benefits in terms of improved and easier monitoring of the MV grid were appreciated by the team at the control centre. The self-healing features were also considered to be very helpful and a time saver.

Further details on the implementation of the field test and the conducted test cases can be found in Appendix E.

CHAPTER 13

# Conclusion and Outlook

The three large trends that challenge the energy sector - decarbonisation, digitalisation, and decentralisation - call for new ways to think and operate the power system. Large parts of these challenges are actually happening in the distribution grid. Approaches to cope with these challenges transform the formerly passive system into some form of "smart grid". This inevitably results in an increased complexity and interdependence with ICT components.

The work of this thesis aims to contribute to the development of new ways to operate the power system. It deliberately acknowledges the increased complexity and proposes the concept of resilience as design principle for a promising way to rethink the grid operation of the future and to handle the complexity. To approach this goal, several scientific outcomes have been postulated in the introduction of this thesis, see Chapter 3. These outcomes have been validated throughout this thesis. In summary, the results of this thesis can be grouped into theoretic results, achievements in implementation and validation efforts.

## Theoretical and Conceptual

From a theoretical and conceptual perspective, this thesis achieved several results. Preparatory efforts led to the definition and stringent classification of architectures for smart grid solutions. This helps to clarify the unsystematic use of key labels for smart grid solutions. Such a stringent definition of architectures was missing before.

Main efforts of this thesis were directed towards the design of an especially resilient outline for the architecture of the grid operation. This includes a resilience analysis of different operation architectures against IT related disturbances and results in the choice for a distributed-hierarchical architecture. This architecture choice was not only validated from a resilience point of view but also from a functional perspective. Analytic and simulation based investigations show that a distributed-hierarchical operation architecture is a valid and advantageous substitution for centralised architectures.

With regard to resilience increasing methods, the design of the self-healing capability is a major aspect. This self-healing capability relies on the distributed-hierarchical architecture and uses an evolving search space to re-establish the supply for the clients affected by a fault. In general, self-healing is a prominent research topic in power engineering. But an approach that finds a new configuration in near real time after the fault and that concentrates on the use of remotely controllable switches to respect the tight time frame for the resupply was not existing before.

Further on, a comprehensive list of methods is investigated to increase the resilience of the grid operation mainly against ICT related issues. Such a comprehensive investigation has not yet been done before.

## Implementation

The major achievement with regard to implementation is the realisation of the distributed-hierarchical grid operation kit. This implementation is based on the conceptual model for an especially resilient operation of the distribution grid. It provides the basic framework for the actors involved in the grid operation and includes communication capabilities and machine-to-machine messaging. It further incorporates an implementation of the self-healing concept and a list of resilience increasing methods. Further on, the implementation includes an application of the BDEW power system traffic light concept as key supervising and control element. According to the knowledge of the author, this was one of the first practical application of the conceptual ideas of the power system traffic light.

As multi-purpose tool to solve all sorts of typical constraints, a heuristic multi-objective optimisation based on a particle swarm approach is implemented. Compared to other optimisation methods, the approach developed in this thesis is especially able to solve deteriorated grid states for situations where classic optimisations fail to propose a solution.

To complement the grid operation, fast fall back strategies by local control methods are provided.

## Validation

With regard to the validation of the proposed solutions, two major efforts were made. The first one is the validation in a special co-simulation based test environment. The second effort lies in the realisation of a large-scale field test. In this field test major aspects of the work of this thesis have been validated by applying them in a European distribution grid. These validations show the quality and practicability and increased the technology readiness levels of the solutions.

## Outlook

As it has been stated before in this work, the author of this thesis is convinced that the automation of the distribution grid is inevitable. The essential decisions that need to be taken are with regard to the extent and type of automation and control as well as with regard to the regulatory framework. Although this thesis develops a distributed-hierarchical system that avoids a control centre like unit, the near future in utilities around the world will most likely be a mixture of different architectures. One advantage of the distributed architecture is that its use can be limited on the parts of the distribution grid that actually require advanced operation capabilities. In the other parts, where the evolution is slower, the installation can be postponed.

The methods and functions of the grid operation developed in this work are rather static, and always exhibit the same behaviour under the same conditions. Its knowledge base is specifically defined and not unlike classic expert systems. This is in line with the expectations of today's grid operators. But future trends in a lot of ICT applications go towards dynamically adapting self-learning systems. To implement such approaches without compromising the reliability is one of the upcoming challenges of research in software and operation development for power systems.

In this thesis, important steps have been taken in the development and implementation of an especially resilient operation for the distribution grid. This thesis paved the way for further investigations on this subject that are about to happen in the context of resilience analysis of infrastructures. Especially the interaction between the power system and the IT system and their mutual influence on the resilience is of increasing relevance. In the future, cyber security will be one of the major issues, not only for the power system but for almost all technical systems that are affected by digitalisation. As it is shown in this thesis, the architecture and the available functions play an important role when it comes to the resilience against such threats. Here, further research is necessary and many lessons still might be learned before an overall conclusion can be given.

The work of this thesis did not stay in the protected environment of academia, but made the first step in the direction of application. However, further validations and demonstrations are necessary to bring the work of this thesis closer to a possible introduction on the market. Especially important for the fail-safe application in a critical infrastructure like the power system will be standardised and comprehensive test and analysis processes, that guarantee the correct behaviour of the new functions in all imaginable operation states.

# APPENDICES

APPENDIX A

# Grid Data

To be able to validate the proposed solutions, several example grids are used as basis for the simulations. This appendix gives an overview over the four grids that are used in this work.

## A.1 Simple 7 Node Test Grid

The first grid is a simple test grid designed for the validation of the multi-dimensional optimisation. It is a 20 kV medium voltage grid with 7 nodes, see Fig. A.1. Node 1 is assumed to

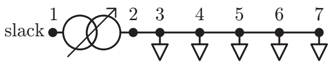



Figure A.1: Scheme of simple 7 node grid to validate the multi-dimensional optimisation.

be the slack node of the system with a nominal voltage of 63 kV. The apparent power basis is chosen to be 100 MVA. The two tables in A.1 give further electric parameters of this grid. The susceptance of all lines is zero.

Table A.1: Grid parameters of simple 7 node grid.

| bus no. | $p_{\text{load}}$ [kW] | $q_{\text{load}}$ [kvar] |
|---|---:|---:|
| 1 | - | - |
| 2 | - | - |
| 3 | 1000 | 400 |
| 4 | 1000 | 400 |
| 5 | 1000 | 400 |
| 6 | 1000 | 400 |
| 7 | 1000 | 400 |

| label | from | to | $r_{\text{pu}}$ [pu] | $x_{\text{pu}}$ [pu] |
|---|---:|---:|---:|---:|
| trafo1-2 | 1 | 2 | 0.2 | 0.5 |
| line2-3 | 2 | 3 | 0.1 | 0.1 |
| line3-4 | 3 | 4 | 0.2 | 0.2 |
| line4-5 | 4 | 5 | 0.1 | 0.1 |
| line5-6 | 5 | 6 | 0.07 | 0.07 |
| line6-7 | 6 | 7 | 0.2 | 0.2 |

For the validation of the optimisation in Section D.3.4 the parameters for the *prosumers* and grid flexibilities are given in Table A.2.

Table A.2: Parameters for the *prosumer* and grid flexibilities of simple 7 node grid.

| bus no. | flexibility type | $p_{\max}$ [kW] | $p_{\min}$ [kW] | $q_{\max}$ [kvar] | $q_{\min}$ [kvar] | initial value |
|---|---|---|---|---|---|---|
| 3 | $P$ | 0 | -2000 | - | - | -400 |
| 7 | $Q$ | - | - | 1000 | -1000 | 0 |

| label | flexibility type | $\text{tap}_{\text{Max}}$ | $\text{tap}_{\text{Min}}$ | dU/tap [%] |
|---|---|---|---|---|
| trafo1-2 | tap position | 10 | 10 | 1.4 |

# A.2 CIGRE Benchmark Grid

This grid originates from the CIGRE Task Force C6.04.02 and was published in [211]. It was especially designed to validate new grid operation concepts under the increasing number of renewable energies. The grid exists in a European and a North American set up, taking into account the particular singularities. In this work the European configuration is used. The grid is operated with a nominal voltage of 20 kV and a system frequency of 50 Hz. Like the other grids used in this work, it is assumed to be balanced between the phases, something that is mostly true for European medium voltage grids. Thus the calculations can be reduced to a single-wire approach. Further on, the grid consists of two 110/20 kV transformers and two feeders. The secondary side (that means the low voltage side) of the transformers is equipped with on-load changing taps. They contain ±16 taps around the neutral position with a d$U$ of 0.625 % per tap.

Fig. A.2 gives a redrawing of the grid structure given in [211]. It shows the standard open-loop configuration, and omits open switches. It also visualises the distributed generators that are used for some of the test cases in this work. The given values for the loads in this grid are peak loads. By choosing the scaling factor low or high load situations can be generated. Thus, two snapshots are created, a low load snapshot with a scaling factor of $sf = 0.02$ and a high load situation with a scaling factor of $sf = 0.8$.

This grid is used for the validation of the multi-dimensional optimisation - Section 9.1.5 - and the local control methods - see Section 9.2.

## A.2.1 *Prosumer* Configuration for Optimisation

The *prosumers* to provide the flexibilities for the optimisation are defined according to the specification given in Table A.3. The flexibilities are provided with a linear price curve, see Section D.3.1 for more details.

## A.2.2 Configuration for Local Control

To validate the behaviour of the local control methods introduced in Section 9.2.1 the *prosumers* with the specifications given in Table A.4 are connected to the grid and are able to provide local control.

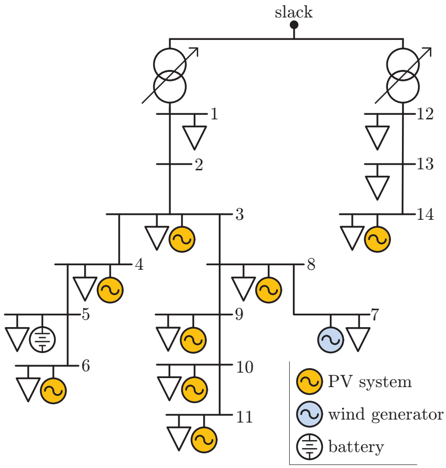



Figure A.2: CIGRE medium voltage benchmark grid; according to [211, p. 34].

Table A.3: Parameters for the flexibility provision of *prosumers*.

| label | bus no. | flexibility type | $p_{\max}$ [kW] | $p_{\min}$ [kW] | minimal power factor | initial value |
|---|---|---|---|---|---|---|
| pvPros3 | 3 | $P$, $Q$ | 0 | -150 | 0.65 | $P = -150\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| pvpros4 | 4 | $P$, $Q$ | 0 | -200 | 0.65 | $P = -200\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| battpros | 5 | $P$, $Q$ | 0 | -600 | 0.65 | $P = 0\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| pvPros6 | 6 | $P$, $Q$ | 0 | -200 | 0.65 | $P = -200\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| windPros | 7 | $P$, $Q$ | 0 | -1500 | 0.65 | $P = -1500\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| pvPros8 | 8 | $P$, $Q$ | 0 | -300 | 0.65 | $P = -300\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| pvPros9 | 9 | $P$, $Q$ | 0 | -250 | 0.65 | $P = -250\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| pvPros10 | 10 | $P$, $Q$ | 0 | -250 | 0.65 | $P = -250\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| pvPros11 | 11 | $P$, $Q$ | 0 | -150 | 0.65 | $P = -150\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |
| pvPros14 | 14 | $P$, $Q$ | 0 | -200 | 0.65 | $P = -200\,\mathrm{kW}$, $Q = 0\,\mathrm{kvar}$ |

Table A.4: Parameters and configuration of local control *prosumers*.

| label | bus no. | $p_{\mathrm{min}}$ [kW] | minimal power factor $\cos \varphi_{\mathrm{min}}$ |
|---|---:|---:|---:|
| pvPros3 | 3 | -150 | 0.95 |
| pvpros4 | 4 | -200 | 0.95 |
| pvPros6 | 6 | -200 | 0.95 |
| windPros | 7 | -1500 | 0.95 |
| pvPros8 | 8 | -300 | 0.95 |
| pvPros9 | 9 | -250 | 0.95 |
| pvPros10 | 10 | -250 | 0.95 |
| pvPros11 | 11 | -150 | 0.95 |
| pvPros14 | 14 | -200 | 0.95 |

## A.3 70 Node Grid

The basis of this grid was first published in [162]. It is a 11 kV medium voltage grid and in its structure quite comparable to European distribution grids. It contains two substations, four feeders, 70 buses and 78 branches. In the original work all these branches represented switches. For the validation of the self-healing approach described in Chapter 10, several of these branches were chosen to be remotely controllable switches (RCS), see Fig. A.3 for the resulting grid. The loads given in the original publication were assumed to be the maximal loads. To generate an average situation, these loads were scaled with a scaling factor of 0.6. The grid area belonging to "substation A" of this grid is also the basis for the simulations done in Appendix C.

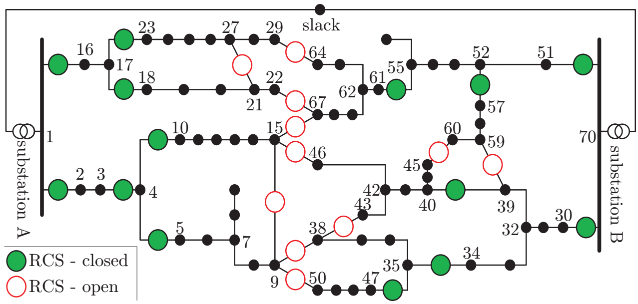



Figure A.3: Self-healing test grid; derived from [162].

## A.4 Real Grid Data

The most realistic grid data was provided by the French DSO *Strasbourg Électricité Réseaux*, as part of the European project "DREAM". The chosen grid data consists of four primary substations and eight feeders from those substations. This area was used in simulations but was also the basis for the field test. It is a medium voltage grid with the nominal voltage of 20 kV. The grid is operated radially, but the substation mutually secure each other via normally open tie switches. Each of the primary substations contains two 63 kV to 20 kV transformers with the nominal apparent power of 36 MVA. These transformers are equipped with on-load tap changers of up to 21 taps. The neutral point of the transformers is impedance grounded. The grid covers a rather rural area with villages and small towns and some industry sites. The total line length of this particular medium voltage grid section is over 250 km, with roughly 30 % overhead lines and 70 % underground cables. Fig. A.4 gives a structural view of the grid. On this scheme no manual switches but only remotely controllable switches (RCS) are visualised. They are named "IPT" for "**i**nterrupteur de **p**ost **t**éléconduit" in French.

The grid area contains several distributed energy resources, mostly small scale PV systems connected to the downstream low voltage grids. Five PV systems ranging from 300 kW to 1000 kW are directly connected to the medium voltage grid, they are displayed in Fig. A.4. Further on, additional specifications for this grid were also given, like the loading limits of lines and cables and the protection characteristics for each of the feeders.

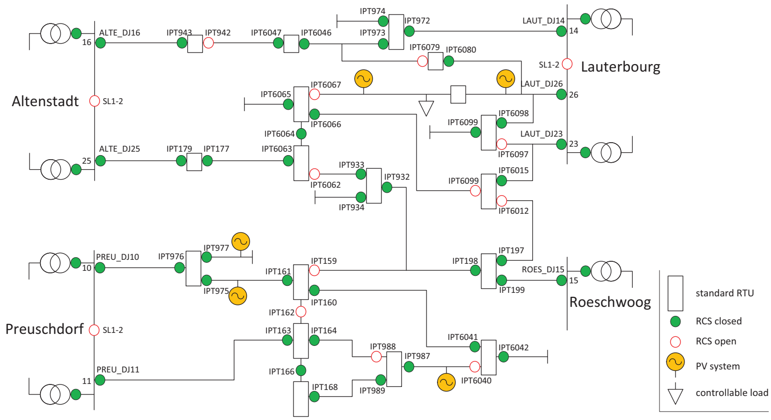



Figure A.4: Structural overview over the field test grid area, including all available RCS.

The loading of the system is very sensitive to temperature and season, as in France electric heatings are common. So the currents in the feeders range from average 20 A in the summer half-year to average 90 A in the winter half-year. What was missing in the provided grid data was the information about the actual load profile and concrete values of all loads for standard situations. But the maximum load procured during a maximal loading situation was given for all loads. Additionally available were measurements of the ten minute average values of the feeder currents for roughly two years. Before using the grid in simulation, the task was to generate approximative realistic values for all loads in the grid. This was done according to the following approach: From the feeder currents, two average currents were calculated. One for the summer period from the 15th of April to the 15th of October $I^{\text{feeder}}_{\text{Summer}}$, and one $I^{\text{feeder}}_{\text{Winter}}$ for the winter period in the other half of the year. This bisection of the year is quite common in power systems. Especially in France the distinction is important, as the loading is substantially higher in winter. By using the maximum power value $P^{i}_{\text{max}}$ of each load $i$, their relative portion $p_i$ to the total maximum power $P^{\text{feeder}}_{\text{max}}$ of the feeder was calculated

$$p_i = \frac{P^{i}_{\text{max}}}{P^{\text{feeder}}_{\text{max}}}. \tag{A.1}$$

Under the (rather strong) assumption that all the loads scale proportionally to this percentage, and by using $I^{\text{feeder}}_{\text{Summer}}$ and $I^{\text{feeder}}_{\text{Winter}}$, an approximative value of every load $i$ of the grid could be calculated with

$$P^{i}_{\text{Summer}} = p_i \cdot P^{\text{feeder}}_{\text{Summer}} = p_i \cdot \sqrt{3} \cdot U_{\text{N}} \cdot I^{\text{feeder}}_{\text{Summer}} \tag{A.2}$$

and analogue for $I^{\text{feeder}}_{\text{Winter}}$. So two approximative but realistic loading situations could be derived. One is suitable to cover the summer half-year, the other to cover the winter half-year.

APPENDIX B

# Tables of Resilience Analysis

This appendix provides the tables required for the resilience analysis of Chapter 6.

Table B.1: Targets, performance indicators, system performance functions and their realisation in different operation architectures. The service functions that are considered in step (5) are marked with a blue background colour.

| Target | Performance indicator | Functions | Local operation architecture | Central operation architecture | Distributed-hierarchical operation architecture |
|---|---|---|---|---|---|
| Equipment loading below rated capacity | Line loading | Reducing loading, shedding of loads or generators, reconfiguration | Theoretically possible but not used in practice as information about admissible loading is specific. | Classic approach by automated functions or human decisions. | Possible with appropriate automated approach. |
| Voltage within tolerance | Voltage profile violations | Voltage control of voltage control units, reactive power control of distributed generators | Is part of grid codes for distributed generators; also used for on-line tap changers. | Set points of voltage control units are defined by control centre. | Possible with appropriate automated approach. |
| Improve supply reliability | System average interruption duration index (SAIDI) / system average interruption frequency index (SAIFI) | Self-healing to resupply loads and generators | Not possible. | Classic approach by automated functions or human decisions. | Possible with appropriate automated approach. |
| Loss reduction | Power losses | Voltage control, reconfiguration of grid | Not possible. | Classic approach by automated functions or human decisions. | Possible with appropriate automated approach. |
| Capability to build a microgrid and to be operated in islanded mode | Islanding capability | Primary and secondary control, grid forming, synchronisation | Primary control is possible through fast frequency control. | Area that is controlled by control centre generally too large to be a microgrid. | Distributed operation units can be used as microgrid controllers. |

Table B.2: Pre-assessment of system functions and disruptions for local operation architecture.

<table>
<tr><th>Disturbance</th><th>Shedding of load or generator</th><th>Voltage control</th><th>Islanding droop control</th></tr>
<tr><td rowspan="2">Tampering on a machine</td><td colspan="3">Effort: Every machine has to be accessed individually and from a geographic proximity, protection on every device is comparatively simple.<br>Tampering requires in depth knowledge about the hardware specific control commands and is thus in general more complex than denial of service disturbances.</td></tr>
<tr><td colspan="2">Impact: Can result in switched off devices but area of influence is limited.<br>Damage on physical device might be possible.</td><td>Impact: Might disturb microgrid operation, as they are generally geographically limited.</td></tr>
<tr><td>Tampering in communication network</td><td colspan="3">Not applicable.</td></tr>
<tr><td>Denial of service against a process or device</td><td colspan="3">Effort: Every machine has to be accessed individually and from a geographic proximity, protechtion on every device is comparatively simple.<br>Impact: Can result in switched off devices.</td></tr>
<tr><td>Denial of service against data flow or communication network</td><td colspan="3">Not applicable.</td></tr>
</table>

Table B.3: Pre-assessment of system functions and disruptions for central operation architecture.

<table>
<tr><th>Disturbance</th><th>Shedding of load or generator</th><th>Voltage control</th><th>Reconfiguration / self-healing</th></tr>
<tr><td rowspan="2">Tampering on a machine</td><td colspan="3">Effort: Control centres are generally rather good protected (physically but also digitally), but as they are very expensive, their equipment is not often renewed and may contain legacy devices. As human beings are involved, social engineering is an option.<br>Tampering requires in depth knowledge about the hardware specific control commands and thus is in general more complex than denial of service disturbances.</td></tr>
<tr><td>Impact: Large scale load or generation shedding; could destroy components if overloaded.</td><td>Impact: Could destroy devices if voltage limits are not respected.</td><td>Impact: Disconnection of wider parts of the grid; might put field workers into danger if open switches are closed.</td></tr>
<tr><td rowspan="2">Tampering in communication network</td><td colspan="2">Effort: Might be relatively simple if the public internet is used to communicate with distributed generators and controllable loads. Tampering requires in-depth knowledge about the hardware specific control commands.</td><td rowspan="2">Effort: Difficult, as switches are generally connected to the private network of the system operator.<br>Impact: Disconnection of wider parts of the grid up to the disconnection of complete distribution grids. Might put field workers into danger if open switches are closed.</td></tr>
<tr><td>Impact: Large scale load or generation shedding; could destroy components if overloaded.</td><td>Impact: Could destroy devices if voltage limits are not respected.</td></tr>
<tr><td rowspan="2">Denial of service against a process or device</td><td colspan="3">Effort: Control centres are generally rather good protected (physically but also digitally), but as they are very expensive, their equipment is not often renewed and may contain legacy devices. As human beings are involved, social engineering is an option.</td></tr>
<tr><td>Impact: No control over generators and loads, inadmissible operation states might occur.</td><td>Impact: No voltage control devices can be activated any more. Could destroy devices if voltage limits are not respected.</td><td>Impact: No reconfiguration can be done any more, clients might stay unsupplied.</td></tr>
<tr><td rowspan="2">Denial of service against data flow or communication network</td><td colspan="2">Effort: Might be relatively simple if the public internet is used to communicate with distributed generators and controllable loads.</td><td>Effort: Difficult, as switches are generally connected to the private network of the system operator.</td></tr>
<tr><td colspan="3">Impact: Control centre is no longer operational, as it might not receive any information and be able to communicate.</td></tr>
</table>

Table B.4: Pre-assessment of system functions and disruptions for distributed-hierarchical operation architecture.

<table>
<tr><th>Disturbance</th><th>Shedding of load or generator</th><th>Voltage control</th><th>Reconfiguration / self-healing</th><th>Islanding droop control</th></tr>
<tr><td rowspan="2">Tampering on a machine</td><td colspan="4">Effort: As devices are widespread over geographic area physical protection is more difficult. Tampering requires in depth knowledge about the hardware specific control commands and thus is in general more complex than denial of service disturbances.</td></tr>
<tr><td>Impact: Loads and generators in a zone can be shed.</td><td>Impact: Could destroy devices in a zone if voltage limits are not respected.</td><td>Impact: Zones can be disconnected from the grid.</td><td>Impact: Disturb microgrid functioning, no intervention from superior level possible.</td></tr>
<tr><td rowspan="2">Tampering in communication network</td><td colspan="2">Effort: Might be relatively simple if public internet is used. But communication should allow peer-to-peer mode and be independent from elements outside the particular are. Thus intrusion requires the physical presence in the zone.</td><td>Effort: Difficult, as switches are generally connected to the private network of the system operator.</td><td>Effort: Difficult, as microgrid requires special communication capabilities.</td></tr>
<tr><td>Impact: Loads and generators in a zone can be shed.</td><td>Impact: Could destroy devices in a zone if voltage limits are not respected.</td><td>Impact: Zones can be disconnected from the grid.</td><td>Impact: Disturb microgrid functioning, no intervention from superior level possible.</td></tr>
<tr><td rowspan="2">Denial of service against a process or device</td><td colspan="4">Effort: As devices are widespread over geographic area physical protection is more difficult. Processors of distributed devices have generally less memory and storage then central servers and are more easily saturated.</td></tr>
<tr><td colspan="2">Impact: Operation unit of zone might be unresponsive. In this case the superior level takes over the operation.</td><td>Impact: Reconfiguration works in peer-to-peer mode, thus if the operation unit of one zone is unresponsive it might find other reconfiguration partners.</td><td>Impact: Disturb microgrid functioning, no intervention from superior level possible.</td></tr>
<tr><td rowspan="2">Denial of service against data flow or communication network</td><td colspan="4">Effort: Communication should allow peer-to-peer mode and be independent from elements outside the particular area. Thus intrusion requires the physical presence in the zone. But bandwidth is limited and might be easily saturated.</td></tr>
<tr><td colspan="3">Impact: Devices and switches in one zone can no longer be controlled, or communication across hierarchy levels is no longer possible.</td><td>Impact: Secondary microgrid control is no longer possible.</td></tr>
</table>

APPENDIX C

# Exemplary Validation of Distributed Operation Architecture

This appendix provides simulations based on an example grid that validate the distributed operation architecture, see Section C.2. However, simulations are also presented in Section C.3 that show the limits of the distributed approach, as feeders under certain circumstances can negatively influence each other, especially if contradicting problems must be solved on neighbouring feeders.

## C.1 Example Grid

The general and with regard to actual numbers rather arbitrary investigations in Section 7.1 are concretised by simulations on an example test grid. They validate for realistic test cases the assumption that feeders can be operated independently but also visualise the limits and how this might affect the grid operation.

The example analysis relies on the grid data of “substation A” of the 70 node grid. A structural sketch of this grid is given in Fig. C.1. Further details, especially of the electrical characteristics, can be found in Appendix A.3.

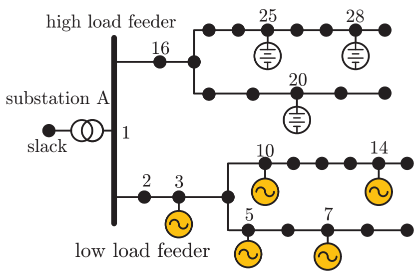



Figure C.1: Example grid for simulation based on data given in [162].

This grid data contains one high to medium voltage substation with two feeders, one starting with node number 2 and the other with node number 16. For the loads on the first feeder starting with node 2 a low load situation with a scaling factor of 0.2 is assumed. Thus this feeder is called the “low load feeder”. For the second feeder starting with node number 16 a high load situation with a scaling factor of 0.8 is assumed. Consistently this feeder is the “high load feeder”. On the “low load feeder” with starting number 2, five distributed generators like PV systems are available. They generally inject their maximal available active power. But this injection could be reduced to solve e.g. voltage problems on the feeder. On the “high load feeder” starting with node number 16, three storage systems are available. In standard configuration, these storage systems are switched of, but they could be used to inject additional active power into the system.

## C.2 Test Case 1: Valid Distribution

In the first test case the transformer of the primary substation is represented by the original impedance values given in the data sheet of the grid. This means a reactance of $X = 0.145\,\Omega$ and a resistance of $R = 0.001936\,\Omega$.

The green plus signs in Fig. C.2 to Fig. C.5 give the initial voltage magnitude along the feeders before any intervention. The amber lines $L_{\text{amber}}$ at 0.975 and 1.025 p.u. give for now the admissible voltage boundaries. Details on these limits are given in Section 8.2. On the "low load feeder" the voltage exceeds the upper boundary values, on the "high load feeder" the voltage falls below the lower boundary voltage. In a first step, an operation unit is assumed that operates the whole substation and the two feeders together. To solve the voltage profile violations an optimisation is used (see Section 9.1) and the use of flexibilities provided by the distributed generators and the batteries is optimised. The resulting voltage is visualised by the orange circles in Fig. C.2. This is realised by reducing the active power injection of the distributed generators on the "low load feeder" and by injecting active power from the batteries on the "high load feeder". With this overall optimisation the voltage along both feeders is back within the admissible margins.

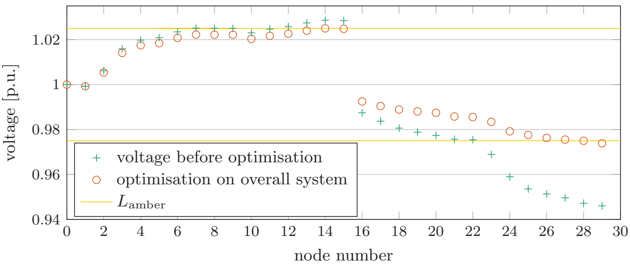



Figure C.2: Voltage profile of grid area of "substation A" before and after optimisation on overall system.

In a second step, each feeder is operated independently. To start with, the "low load feeder" is equipped with an operation unit. The view of this operation unit is limited on the "low load feeder", it does not get any information from the other feeders. Fig. C.3 visualises the voltage profile seen by this operation unit of the "low load feeder". Based on this profile, an optimisation is performed to solve the voltage profile violations. This results in the reduction of the injection of active power by the distributed generators. The lavender asterisks indicate the solution found by the "low load feeder" operation unit. This result of the optimisation, that means the new set points of the distributed generators that decreased the injection, is then established. Fig. C.4 visualises the effect, the "low load feeder" optimisation has on the overall system. It is clearly visible that the "high load feeder" stays more or less unaffected, and the resulting voltage in the "low load feeder" is approximately the one resulting from the optimisation of the operation unit on the feeder. Thus, for this case, the assumption of "small" impedance of transformer and bus bar holds and the voltage on the "high load feeder" is not influenced by the changes in the power flow along the "low load feeder". This is especially

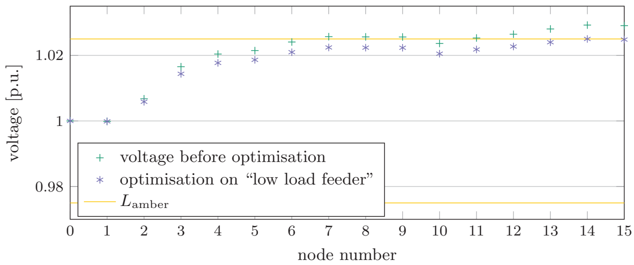



Figure C.3: View of operation unit on "low load feeder".

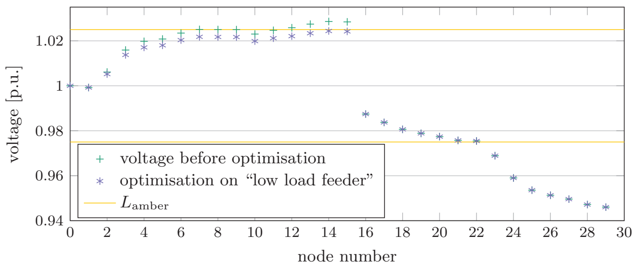



Figure C.4: Effect of the optimisation on the "low load feeder" on the overall system.

important for situations like the one in this test case with opposite loading situations on the two feeders. Because in such a case, influencing the "high load feeder" by the result of the optimisation in the "low load feeder" would mean to worsen the situation, and to increase the under voltage. Further on, the comparison of the set points of the distributed generators on the "low load feeder" calculated by the global optimisation with the set points found by the operation unit on the "low load feeder" shows that approximately the same results are found.

The same behaviour can be validated for an independent optimisation on the "high load feeder", see Fig. C.5. The increased injection of the batteries solves the voltage along the "high load feeder" but does not influence the "low load feeder".

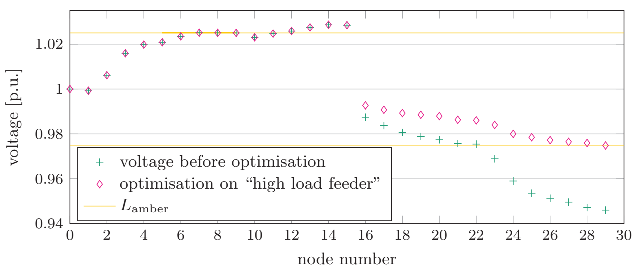



Figure C.5: Effect of the optimisation on the "high load feeder" on the overall system.

A nice side effect of this distribution is that the optimisation for each of the feeders independently and in parallel is faster than the overall optimisation. This results on the one hand from the reduced search space, as only the flexibilities available on the feeder are considered. On the other hand, optimisations on the power system generally require the repeated solving of the power flow equations. As the grid area is reduced, the computation time required for the solving of the grid equations decreases. The concrete numbers can vary depending on the type of optimisation and the implementation. But for the case considered in this work the optimisation on the overall system takes about 4 s, the optimisation on the "low load feeder" 700 ms, and the optimisation on the "high load feeder" 300 ms.

## C.3 Test Case 2: Invalid Distribution and Suggestions for Correction

In a second test case the resistance of the transformer is increased by the factor of 1000 and becomes $R = 1.936\,\Omega$.

As in the previous test case, the operation unit on the "low load feeder" optimises the voltage profile along its feeder, see Fig. C.6 the green plus signs for the initial values. The voltage profile violations are solved again with the optimisation developed in Section 9.1. This optimisation requests that the injection of the distributed generators on this feeder has to be reduced. The calculated resulting voltage that is found by the operation unit of the "low load feeder" is given with lavender asterisks in Fig. C.6.

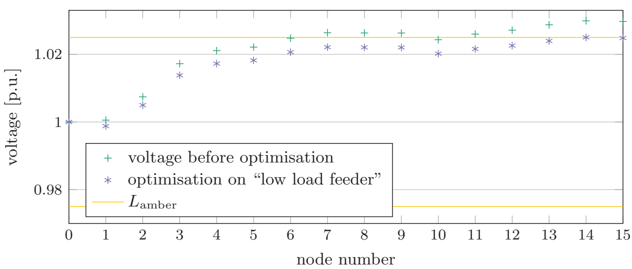



Figure C.6: View of operation unit on "low load feeder".

Now it is assumed, that this solution is established. In Fig. C.7 the lavender asterisks visualise the resulting voltage profile along the two feeders if the solution found by the operation unit of the "low load feeder" is realised. It is clearly visible that the reduction of the injected power of the distributed generators on the "low load feeder" results also in a voltage drop along the "high load feeder". As on this feeder the voltage is already low, this aggravates the situation. This is in contrast to the results visualised in Fig. C.4 with the low transformer resistance, where the voltage on the "high load feeder" is unaffected. If now the operation unit on the "high load feeder" on its turn optimises its voltage profile and request an increase of the injection of the batteries, this would undo the effects intended by the optimisation on the "low load feeder". The two feeders would counteract each other, playing some sort of "electric ping-pong". This is no stable operation, and must be prevented.

A possible solution to this can be to extend the distributed system by a hierarchical structure. A superordinated operation unit, e.g. supervising the primary substation and all feeders

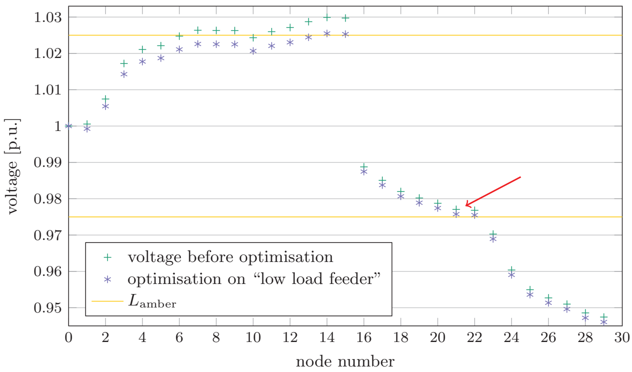



Figure C.7: Effect of the optimisation on the "low load feeder" on the overall system. The voltage drop on the "high load feeder" increases because of the changes in the "low load feeder".

connected to it, can detect such "swinging" between feeders and can intervene. Such an intervention could be the overall optimisation of all feeders together.

All these investigations have been done based on changes on the resistance and the active power injection and consumptions. The analogue behaviour can be simulated for the reactance and the reactive power. As the reactances of transformers are often larger than the resistance, the situation might even be more critical.

# APPENDIX D

# Simulation Environment

This appendix gives details on the practical implementation of the distributed grid operation and the particular methods specialised for the simulation based validation of the concepts proposed in the main body of this work.

Section D.1 introduces the general implementation of the distributed grid operation kit that builds the frame for the new functionalities developed in this work. The implementation of more power system related aspects is described in Section D.2 and details about the specific implementation of functions can be found in Section D.3. Further on, a special test environment was set up to test as realistically as possible the interaction of the actors of the grid operation. This is described in Section D.4.

## D.1 Distributed Grid Operation Kit

What is called here the distributed grid operation kit is basically the implementation of the grid operation architecture described in Section 7.2. Instead of using pre-build frameworks like JADE [93] for its realisation, the grid operation is implemented in a new environment. This was necessary in order to be able to control all aspects related to the behaviour of the agents, especially their communication. This distributed grid operation kit and all other functions in this chapter unless explicitly indicated are implemented with the programming language Java. Thus, it follows a very object-oriented approach and uses multi-agent guidelines for the implementation. This first section gives a general overview over the components of the grid operation. It omits deliberately aspects related to power system analytic, they are described in Sections D.2. It also omits detailed information about the implementation of specific actor functionalities. This is given in Section D.3.

### D.1.1 Actors

Each of the actors of the grid operation is realised as an independent agent, according to the definition of the term in Section 4.3.1. All actors that are part of the implemented grid operation kit have a common abstract superclass called `Agent`. This designs them as independent threads that are able to run independently from each other. Further on, this class provides basic functions like logging and communication mechanisms. From this superclass all other agents are derived. As described in Section 7.4, the three main types of agents are the *DSO agents*, the *prosumer* and the *aggregator*. The code for these agents is written as general as possible, while all specific parameters are defined by an external configuration file. These configuration files are structured in JavaScript Object Notation (JSON)-Format [212]. This allows the serialised representation of complex Java objects, as well as the creation of Java objects based on the configuration files. For this purpose, the Java library `Jackson JSON Processor` [213] is used.

### DSO Agents

Based on the abstract superclass `Agent` an abstract subclass called `DSOAgent` is implemented. This class contains specific functions and attributes for *DSO agents*, like the grid data. From this both the `CellDSOAgent` and the `SubstationDSOAgent` can be derived. These classes contain the core functionalities related to the DSO, like the analysis of the grid state, the optimisation, the self-healing etc. These abstract classes then are implemented either for the simulation or for the field test, specifying for example the way in which measurements are collected. Fig. F.3 in Appendix F gives an example of the inheritance between the classes for the actor *substation DSO*.

### Prosumer

The functions concerning the *prosumer* are only implemented as far as they concern the interaction with the grid operation. Concepts like the optimisation of self-consumption or other economic models are not considered. Also internal electric models, like generator or PV models are not considered. Their key electrical behaviour is described by the set points of active and / or reactive power. This can be either positive (e.g. for active power loads) or negative (e.g. for active power generation). The initial operating points can be either defined statically by the configuration file or as described in Section D.1.5 as time series that are managed by the *grid simulator*.

The implementation distinguishes mainly two types of *prosumers*: the `LoadProsumer` and the `PVProsumer`. The `LoadProsumer` represents controllable loads. It assumes a discrete flexibility provision, as loads generally can not take all possible values, but only a certain set (e.g. washing machine is on or off). The `LoadProsumer` does not provide reactive power flexibilities. The `PVProsumer` represents distributed generators, mainly PV systems. Within limits, it can provide quasi-continuous reactive and active power flexibilities. The `PVProsumer` also includes the local control capabilities.

## D.1.2 Aggregator

The *aggregator* is implemented in a very generic and simple way. As it is a pure software actor that only needs to interact with other actors and not with the physical environment of the power system only one class is necessary, the `AggregatorAgent` that is also a subclass of `Agent`.

As described in Section 8.2, in every time step, the *aggregator* contacts the *prosumers* and requests their flexibilities. As soon as all *prosumers* have provided this data, or after a certain dead time, the *aggregator* aggregates the flexibilities. Here one could imagine approaches that include an internal optimisation to maximise the asset for the *aggregator*. But this is out of scope of the work of this thesis. Thus, the implemented `AggregatorAgent` simply creates a list with all available flexibilities. If a *DSO agent* activates some flexibilities, the `AggregatorAgent` splits the list of requested set points according to the *prosumer* they belong to. It then sends the set point, or set points, if the *prosumer* provides more than one type of flexibilities, to the particular *prosumer*.

## D.1.3 Communication

The communication between the actors of the grid operation is a crucial aspect for the design of a distributed operation system. The choice was taken for the XMPP protocol. XMPP stands for extensible messaging and presence protocol. It is a protocol requiring a client-server architecture and allowing a near real-time communication [214]. XMPP is especially considered for machine to machine communication [215]. More concretely, it is considered as a suitable protocol for the data models defined in IEC 61850 [216]. And IEC 61850 is a leading standard for substation automation. But for the case of simplicity, IEC 61850 was not used as data model in this work. Instead, serialised Java-objects in JSON format are exchanged between the agents. These objects are all instances of a class called `Message`. Several subclasses of `Message` have been implemented for different types of messages. Fig. F.4 in Appendix F gives an UML class diagram for the message classes. This serialised object is stored in the "body" of the XMPP message. Further on, each XMPP message contains a subject. According to the subject, the messages are treated differently. Each subclass of `Agent` can connect itself with a user name and a password to a XMPP server. This information is coded in the configuration file for the agent. Before sending the first message, the agent opens a so called "Chat" with desired communication parters.

To realise the communication structure as it is described in Section 11.2.1 each agent can connect itself to two different XMPP severs, one local and one global server.

All this is realised by using the Java library `Smack` [217]. The XMPP server is realised with `Openfire` software [218].

### D.1.4 SCADA

To supervise the simulations, a point is required where all information is collected. This is realised by an agent called `SCADA`, as it takes over roughly the same functions as a real SCADA would do. It keeps track of the agents that are operational and all status information is sent to the `SCADA`. Further on, the execution of functions can be triggered from it, as it can send command messages to the other agents. The *SCADA* can be combined with a graphic user interface (GUI). This was especially used for the field test, see Section E.2.1, but it was also applied for the simulations.

### D.1.5 Grid Simulator

The `GridSimulator` also inherits from the `Agent` superclass. Its core input data is the grid data of the complete grid area under consideration, see Section D.2.1. Based on this grid data, a power flow calculation method is available, see Section D.2.3. Agents requiring grid measurements can request them from the `GridSimulator`. This replaces the readout of sensors. If *prosumers* change their set point (due to local control or optimisation) they can feed back the new set point to the `GridSimulator`. Thereupon the `Gridsimulator` also modifies the particular value and re-performs a power flow calculation. It thus gives always a coherent image of the values assumed by the grid operation. The `GridSimulator` supports also the simulation of time series of load and generation data. This can be used to simulate the behaviour of the grid operation over changing conditions. For this, the list of values for each load or generator can be read in. At every new time step this leads to a new load or generator output for the particular node of the grid. The intervals of the time steps can be chosen at will.

To simulate faults as required for the self-healing described in Section 10.4, the `GridSimulator` can be triggered to represent a specific fault situation. Also the outage of the complete grid can be triggered by setting the slack node to zero.

For the test environment that is introduced in Section D.4, the `GridSimulator` provides its measurements via the "Message Bus", as visualised in Fig. D.6. To simplify the debugging of code at an earlier state before going into the comprehensive test environment, it is also possible to send the measurements via the XMPP communication channel.

### D.1.6 Ancillary Functions

To complete the distributed grid operation kit, several ancillary functions have been implemented. They are described in the following list

**Synchronisation** To allow the synchronisation of distributed actors, the Christian's algorithm has been implemented [219]. The time server, called `MasterClock` is running as additional function in the `SCADA`. Every agent can send request to this time server and update its own time accordingly.

**Graph Plotting** For the analysis of results the plotting of graphs is possible. This is realised by using the library `JFreeChart` [220]. Fig. D.1 gives a screenshot of such a graph. It represents the voltage profile along the feeder before and after an optimisation.

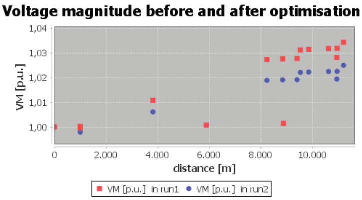



Figure D.1: Screenshot of voltage profile plotting.

## D.2 Functions for Power System Analysis

There already exist a wide range of proprietary or free solutions that allow the analysis of the electrical behaviour of power systems. To be able to use the required functions from within the Java framework, some aspects of classic power flow analysis needed to be adjusted, refined or newly implemented. This section presents the efforts made to realise the required functions. It starts with Section D.2.1 that describes the modelling of the grid data. This required functions to derive the particular grid data that is required as input data for the respective actors of the grid operation. The implementation of these functions is described in Section D.2.2.

Key function to simulate and predict the steady-state behaviour of the power system is the possibility to numerically solve the power flow equations. How this is implemented is described in Section D.2.3. Section D.2.4 describes the implementation of the state estimation of the power system. Such a state estimation can be used to derive the most complete view on a certain situation based on a set of measurements of the power system.

### D.2.1 Data format of Grid Data

The structural and electrical data related to particular grid fraction is the most important data base. This grid and its components are represented as single-phase steady-state models. The data format developed in this work bases upon the common "matpower" data format [127] as well as the old French standard "PRAO" to model distribution grids [221].

The slack node is generally placed at the high voltage side of the primary substations. The per-unit system is used to store most of the parameters required for the calculations. Loads are modelled as constant power loads and are assigned to a particular node of the grid. Apart from an identifying number, a node can have further attributes like the value of the load and / or generation assigned to this node, the priority indicator of the load, and the minimal and maximal admissible voltage.

Lines and transformers are modelled according to the $\pi$-equivalent circuit [39, p. 468]. This electric data is stored in elements called "segments", that generally describe the connection between two points. Apart from the electric data, segments include information about the start and the end point of the connection. They also include further information about the type of connection, if the segment is a line, cable, transformer, switch or circuit breaker. Switches can be further specified, if they represent manual or remotely controllable switches (RCS). Segments that represent open switches are stored apart. They are omitted for power flow analysis but required as input for the reconfiguration.

Apart form this electric model of the grid, a graph based model is available that allows investigations of the structure of the grid like the connectivity or the distance between two nodes. This is especially required for the implementation of the self-healing, see Section D.3.5.

From an implementation perspective, the grid data is stored in a class called `Grid`. This class also contains objects like the power flow solver, see Fig. F.5 of Appendix F for an UML class diagram. On the hard drive the grid data is stored in serialised JSON-Format [212].

### D.2.2 Structuring of Grid Data

The grid data that is used for the work of this thesis is generally provided as comprehensive data set for all nodes and connections in the considered grid area. According to the structural elements introduced in Section 7.3 this data needs to be processed before it can be used as input data for the particular actor on a certain element. This step mainly required the automated finding and assembling of required data for the *elementary cells* and the *substation federations*. This means, the *cell DSO* requires as input data the grid model of its cell and the neighbouring connections, the *substation DSO* requires the grid model of all the *elementary cells* that build its *substation federation*. The input data for this step is the comprehensive grid data, originating from different sources. The output are JSON-files for each of the actors that contain the particular share of the comprehensive grid data modelled as described in the previous section. Th input for the algorithm are the grid topology represented as graph $G$ and the list of nodes that define the beginning of the feeders of the particular primary substation. Based on a modified Depth-first search the grid graph $G$ is explored, see [222, p. 603-606] for an introduction into the Depth-first algorithm. For a node $u$ all adjacent edges are identified. But instead of simply traversing the graph, each adjacent edge $e(u, v)$ is investigated before adding the associated node $v$ to the stack of unvisited nodes. If the edge represents a "normal" line or cable or a closed switch that can only be operated manually, the Depth-first search continues normally, adding the visited node to the list of nodes of an *elementary cell*, and the edge $e(u, v)$ to the list of connections of the *elementary cell*. But if the edge represents a remotely controllable switch that is closed, this defines the end of an *elementary cell* and the start of a new one. In this case, $v$ is added to the stack, but a new list for the nodes of an *elementary cell* is started. If the edge represents a remotely controllable switch that is open, this also defines the end of an *elementary cell*. But in this case $v$ is not added to the stack but the edge $e(u, v)$ is saved in the open switch list. If $v$ can be reached via closed switches from the same substation by another path it represents an "intra-substation open switch". Otherwise, and this means that $v$ is not supplied by the substation under investigation, it represents an "extra-substation open switch". These two terms are introduced in Section 10.2 and are key for the self-healing approach.

### D.2.3 Power Flow Calculation

Power flow calculations are an important function for various aspects of the grid operation and its simulation. It is required for the validation of solutions for the optimisation - Section 9.1 - and the self-healing - Section 10. Further on, it is required for the `GridSimulator` described above in Section D.1.5. When performing power flow calculations, the objective is to find the steady-state behaviour of the grid. This means to find the voltage (magnitude and angle) $V$ for each node in a given grid, under a given load and generation pattern

$$I_{\text{bus}} = Y \cdot V. \tag{D.1}$$

The matrix $Y$ is the admittance matrix and $I_{\text{bus}}$ the vector of bus currents. This equation has a linear structure, but generally the bus currents are not known. With $I = \frac{S}{V}$ they depend on the voltage. For alternating currents this can not be solved analytically. Instead iterative methods are used. For this work, two types of power flow solvers were implemented. One is the most common method to solve the power flow problem. It uses an Newton-Raphson method to approximatively find a solution. The Newton-Raphson power flow implemented for this work is based on an implementation proposed by [223]. The advantage of this method is that it can solve the power flow even for meshed grids. Disadvantage is that it requires the inversion of a matrix with dimension $n \times n$ with $n$ the number of buses in the grid. This means the runtime of this method scales with $\mathcal{O}(n^2)$. Especially for the power flows required for the evaluation of the self-healing functions, it is always guaranteed that the grid that needs to be evaluated has a radial structure. For this case the backward-forward sweep method is implemented. It advantageously scales with $\mathcal{O}(n)$ and does not require a matrix inversion. Its implementation follows the descriptions given by [224], [225]. Also preliminary work of Niki Kechagia from G2Elab in Grenoble, France was used. Compared to other power flow solvers these two implementations are rather slow as Java is not the best language to implement matrix operations.

### D.2.4 State Estimation

The state estimation is another important function for the grid operation. Based on a set of measurements the grid state, that means the voltage angle and magnitude at every node in the grid, can be calculated. As described in Section 7.4, the state estimation is implemented using the weighted least squares method. This method - known in statistics for several centuries - is introduced by the authors of [226] as a method for state estimation in power systems. The implementation in this work follows the approach described in [105]. The objective of the state estimation is to minimise the following function $J$

$$J\left(\vec{x}\right) = \left[\vec{z} - \vec{h}\left(\vec{x}\right)\right]^T R^{-1} \left[\vec{z} - \vec{h}\left(\vec{x}\right)\right] \tag{D.2}$$

with

- $\vec{x}$ the vector of the unknown grid states (voltage angle and magnitude),
- $\vec{h}\left(\vec{x}\right)$ the estimated measurement function expressed as function of the state variables,
- $\vec{z}$ the vector of measurements,
- $R$ the matrix of the standard deviations of each measurement.

This classic state estimation approach normally requires an over-determined system, with more measurements than unknown variables. Although this holds for the transmission system, it is generally not the case for the distribution system. So two additional types of measurements are introduced, pseudo and virtual measurements [105, p. 6]. Pseudo measurements are estimated values for measurements that are not available, like the active and reactive power demand of substations and clients that do not provide telemetry possibility. When including these estimated values into the state estimation, it is important to assign them a high variance. Virtual measurements are generally generated for buses that never have any loads. For them one surely knows that the active and reactive power set point is zero. This type of measurement can be assigned a low variance as their behaviour is very sure.

Fig. D.2 visualises the voltage profile of the CIGRE benchmark grid introduced in Appendix A.2. A high load situation is assumed. The figure shows the voltage profile for the full knowledge situation as it results from the power flow and the voltage profile as it is calculated by the state estimation. The measurements assumed for the state estimation are the active and reactive power flows over the transformers, the voltage magnitude at the low voltage side of the transformer, and the voltage magnitude at two nodes in the grid: at node 5 and node 13. As node 2 has no loads, virtual measurements are available. Additionally, for all other load nodes an active and reactive power assumption is made around the actual value as it could result from ten minute averages of smart meters.

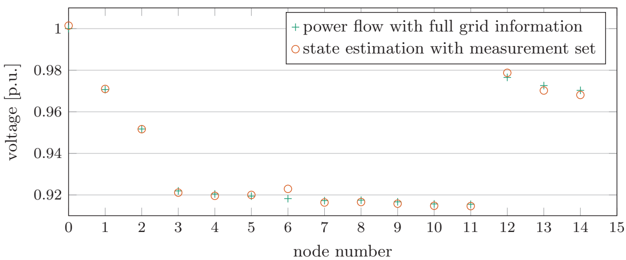



Figure D.2: Voltage profile resulting from power flow (green plus signs) and state estimation on CIGRE benchmark grid with high load situation (orange circle).

## Bad Data Detection

For the bad data detection two methods are implemented as described in Section 11.2.2. The $\chi^2$-distribution test is implemented by relying on the library `ChiSquaredDistribution` of [227]. This API provides a function that, given the degree of freedom, a particular value results from a $\chi^2$-distribution. By comparing this probability with a threshold probability (here higher 95 %) the measurements can be checked for bad data.

The normalised residual test is also implemented. The residual covariance matrix $\Omega$ is calculated according to the description given in [105, p. 113]. The required input matrices are already calculated during the state estimation process.

## D.3 Implementation of Actor Functionalities

This section describes the implementation of major functions of the actors if they have not yet been described elsewhere. It covers the provision of flexibilties by the *prosumers* in Section D.3.1. The implementation of local control for generators and the transformer tap control are described in Section D.3.2 and Section D.3.3 respectively. It also gives in Section D.3.5 some information about the implementation of self-healing specific functionalities.

### D.3.1 Flexibility Provision

Two types of flexibility were implemented as described in Section D.1.1: the discrete flexibilities and quasi continuous flexibilities.

Flexibilities are implemented by the Java class of the same name. This class contains the information about the type of flexibility and the identifier of the node the flexibility is belonging to. Further on, a flexibility is defined by a list of possible set point values and the corresponding list of prices for the use of this flexibility. For discrete flexibilities, this list of set points and the corresponding prices are directly defined externally in the configuration file.

The provision of quasi continuous flexibilities is defined by the minimal and maximal value the set points can take. As the optimisation developed in Section 9.1 needs a list of discrete values, a quasi continuous list contains 1000 elements. Price curves assigned to these set points could take a wide range of forms. As part of this work, a linear and quadratic price curve have been implemented. Apart from the gradient $m$ that is the price per kW or kVar, the zero price point is required. This point defines the standard set point that would be optimal for the *prosumer* from an operational point $P_{\mathrm{Z}}$ / $Q_{\mathrm{Z}}$. The linear price curve is thus defined according to

$$p\,(P) = |P \cdot m - (m \cdot P_{\mathrm{Z}})| \tag{D.3}$$

with $m$ the price per kW deviation from the nominal value $P_{\mathrm{Z}}$. The price curve for reactive power can be constructed accordingly. The quadratic price curve takes the following form

$$p\,(P) = m \cdot P^2 - 2 \cdot m \cdot P_{\mathrm{Z}} + m \cdot P_{\mathrm{Z}}^2, \tag{D.4}$$

and the prices for reactive power can be calculated accordingly. In Fig. D.3 these two types of price curves are visualised.

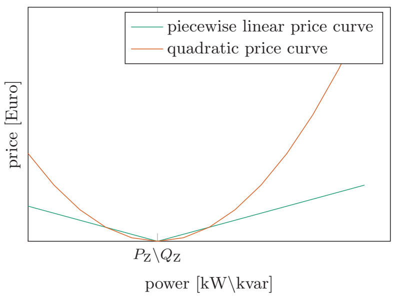



Figure D.3: Linear (green) and quadratic (orange) price curves for *prosumer* flexibilities.

### D.3.2 Implementation *Prosumer* Local Control

The local control functions described in Section 9.2 needed to be implemented to be available in simulation. For the local control functions of the *prosumers* the implementation follows the preliminary work of the master thesis of Franziska Meyer [D16]. The implementations of the fixed power factor $\cos\varphi_{\text{fix}}$ method as well as the Watt-Var control $\cos\varphi\,(P)$ can be realised easily by adding an additional statement that sets the reactive power according to one of these methods. But to simulate the behaviour of the looped feedback controllers as they are used for the $Q\,(V)$, $P\,(V)$ and $P\,(f)$ method an iterative simulation is required. According to [84], [D16] the reactive power set point in iteration $i+1$ can be calculated with

$$Q_{i+1} = Q_i + \frac{Q_{i+1}(V) - Q_i}{\alpha}. \tag{D.5}$$

In this equation $Q_i$ is the reactive power set point in the previous iteration and $Q_{i+1}(V)$ can be derived from the characteristic given in Fig. 9.4 depending on the voltage at the point of common coupling. $\alpha$ is a damping coefficient to avoid oscillations. In this work it is chosen to be 4. The iteration stops if the difference between $Q_i$ and $Q_{i+1}$ is smaller than a given threshold. This approach for the $Q\,(V)$ method is equivalently used for the $P\,(V)$ and $P\,(f)$ method.

### D.3.3 Implementation of Local Tap Changer Control

The local control of on-load tap changers is implemented as an optional function for the *substation DSO*. It follows the description given in [84, p. 37f.], but is realised with one simplification. The integral over a certain time period is replaced by a time interval: If the voltage violates the threshold values longer than a given time interval then the tap is activated either increasing or decreasing the voltage.

Required parameters for the tap changer control are the upper and lower limit of the death band $V_{\text{upper}}$ and $V_{\text{lower}}$, the number of possible tap positions both in positive $n_{\text{tap+}}$ and in negative $n_{\text{tap-}}$ direction away from the neutral position and $\mathrm{d}U$ the percental shift in the voltage per tap. With this data a list of possible tap positions *taps* is generated. This list contains $n_{\text{tap list}} = n_{\text{tap+}} + n_{\text{tap-}} + 1$ elements. The neutral position $taps(n_{\text{tap-}} + 1)$ has the value of 1. The reductions of the tap are calculated with

$$taps\,(i) = 1 - (n_{\text{tap-}} - i) \cdot \mathrm{d}U, \tag{D.6}$$

and the increasings analogue. If the voltage at the secondary side exceeds the upper limit $V_{\text{upper}}$ for a certain time, the tap is increased by one step. And if the voltage falls below the lower limit $V_{\text{lower}}$ for a given time, the tap is decreased by one step.

Fig. D.4 visualises the effect of local on-load tap changers in the two transformers of the CIGRE benchmark grid with high load configuration. Details on the grid can be found in Appendix A.2. The specification of the two tap changers at the transformers in the branch between node 0 and node 1 and the branch between node 0 and node 12 are according to the original grid data described in Appendix A.2. Additionally, it is assumed that the dead band for the reference voltage is $\pm 2\,\%$ around the nominal voltage. This value is proposed by [84, p. 49.]. This means that the tap changer tries to keep the voltage at its secondary side within this bandwidth. For the result visualised in Fig. D.4 the transformer between node 0 and node 1 chooses a tap of 0.9875 (thus two positions away from the neutral position) and the transformer between node 0 and node 12 a tap of 0.99375 (one position away from the neutral position). This increases the voltage along the feeders. But as only the voltage of the node directly behind the transformer is considered, the voltage drop along the feeder still might exceed admissible limits, like in the example given in Fig. D.4. Attention must be paid when operating OLTC in local mode together with local control of PV systems. This can lead to unintended interactions [228].

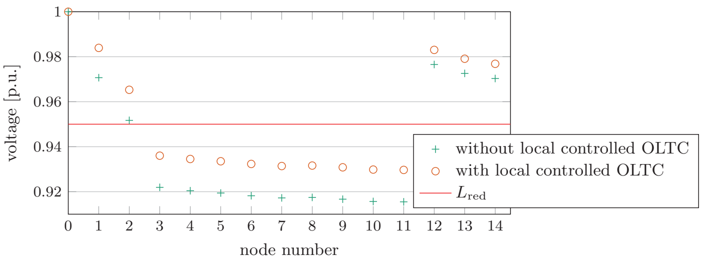



Figure D.4: Voltage profile of CIGRE benchmark grid high load situation with (orange circles) and without (green plus signs) local controlled OLTC.

## D.3.4 Heuristic Optimisation

The particle swarm optimisation (PSO) is implemented according to the description given in [125]. For the heuristic optimisation high quality random numbers are required [125, p. 49]. The built-in Java random number generator is know to have a weak quality. Thus the Xorshift-Algorithm is implemented instead [229]. It is a fast and simple alternative with better statistical behaviour.

A simple grid is chosen to validate the general behaviour of the optimisation. The green plus signs of Fig. D.5 give the voltage profile of the 7-node test grid described in Appendix A.1. As can be seen, the amber low voltage limit $L_{\text{amber}}$ at 0.975 p.u. is violated for most of the nodes in the grid. Two *prosumer* flexibilities are available, see Table A.2 in Appendix A.1. The orange circles and the purple asterisks in Fig. D.5 visualise the voltage profile after the optimisation by using these *prosumer* flexibilities. The difference between these two results is that the weighting of the flexibility price parameter $f_{\text{price, weight}}$ is much higher in the solution represented by the orange circles than in the solution represented by the purple asterisks. Thus the optimisation finds different solutions: the solution represented by the orange circles is archived with $f_{\text{price, weight}} = 1000$. It only applies the reactive power flexibilities (reactive power set point of *prosumer* at node 7 is -1000 kVar) and leaves the active power flexibilities of node 3 untouched. The solution represented by the purple asterisk also relies on the (much more expensive) increase of active power power injection. For this test case $f_{\text{price, weight}} = 5$ is assumed, and the solution activates reactive power of -996 kVar on node 7 and active power of -2000 kW at node 3. The first configuration does not solve the voltage issue, while the second almost achieves a complete correction. In the third test case also the tap position of an on-load tap changer is available as grid flexibility, see Table A.2. The voltage profile resulting from this configuration is visualised by the magenta diamonds. In this solution only the tap position is modified as it is both the cheapest and the most effective solution, resulting in a tap of 0.972 and thus increasing the overall voltage level on this grid. This solution is found with high and low price weighting. The optimisation finds the solutions in less than a second. Because of the random numbers involved in the PSO, the optimisation for every test case is

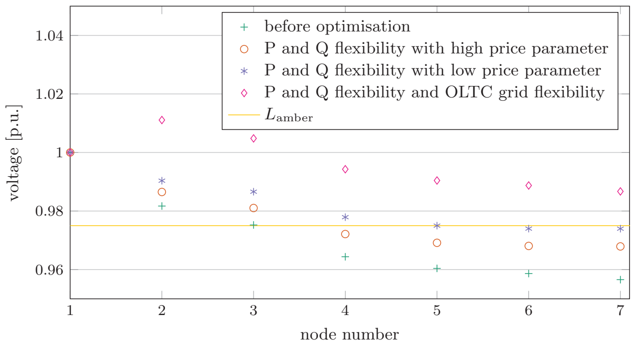



Figure D.5: Three test cases to validate the behaviour of the optimisation on the 7 node test grid.

executed several times. For a constant swarm size of 25 the first test case requires around 100 iterations, the second around 80 and the third around 100. In every run, every test case converged on approximately the same result. This shows the stability of the optimisation. For experienced professionals these solutions to these situations are obvious but as the heuristic optimisation has no previous knowledge about the system these test cases validate the fitness function formulation.

### D.3.5 Self-Healing

The representation of grids in form of mathematical graphs is implemented base don the Java graph library `JGraphT` [230]. This library contains already optimised algorithms for the finding of a fundamental set of cycles in the graph - implemented according to [176] - the Dijkstra's algorithm to find the shortest paths, and methods to test the connectivity of a graph. The power flow calculation is implemented according to the backward-forward algorithm see Section D.2.3. As the grid resulting from the reconfiguration must be radial, this fast and advantageously scaling power flow can be used.

## D.4 Test Environment Design

The left part of Fig. D.6 shows schematically a fraction of a medium voltage grid. The two actors of the grid operation, the *substation DSO* and the *PV prosumer* run on devices physically located either in the substation or at the prosumers premises. Measurements like voltage, current and frequency or status information like the state of switches are directly available through sensors. Whatever happens to the communication between the actors of the grid operation (visualised as dashes purple lines), this local information is always available and can be used for local control actions. In the test environment the geographic separation of the actors is realised by executing them on separate virtual machines. Here the virtualisation solution `VirtualBox` is used [231]. Also the XMPP communication server as well as the *grid simulator* are hosted on virtual machines. The *grid simulator* is further detailed in Section D.1.5. The XMPP server in use is the open source implementation `Openfire` [218]. To provide the actors with their particular local information about the grid, a message bus connects the *grid simulator*

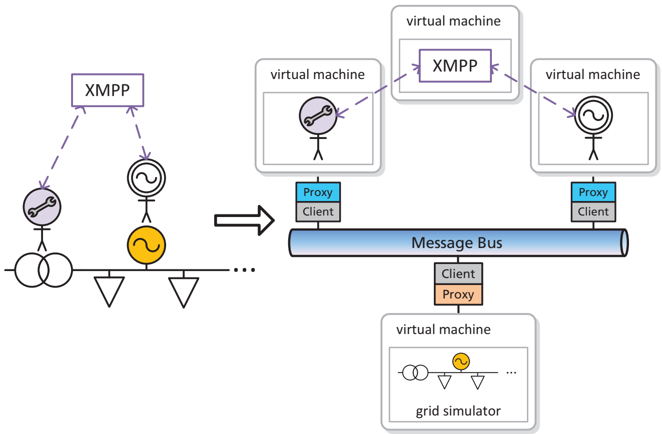



Figure D.6: Transition from the real system to the co-simulation test environment.

with the actors. This message bus relies on the co-simulation platform OpSim [208], [209]. This second possibility to exchange information is only used for the provision of information that in a real installation would result from sensors etc. Thus, only the specific part of the implementation of the actors, that depends on sensor protocols and data acquisition, differs between the simulation and the use in the field.

The quality of this test environment can be seen by means of the Open Systems Interconnection model (OSI model). The seven layers of this model define specific tasks necessary to allow the communication. As can be seen in Table D.1, only the two lowest layers (the physical and the data link layer) differ in the test environment from the field set-up described in Appendix E.

Table D.1: OSI layers comparison of communication in test environment and in the field.

| Layer | Simulation | Field |
|---|---|---|
| Application | XMPP | XMPP |
| Presentation | | |
| Session | | |
| Transport | TCP | TCP |
| Network | IP | IP |
| Data link | Ethernet, IPC Sockets | Ethernet, power-line, WiFi,... |
| Physical | | |

APPENDIX E

# Validation through Realisation in Field Test

This appendix gives details on the realisation of the field test at the French DSO *Strasbourg Électricité Réseaux*. It describes in Section E.1 the outline and architecture of the field test and in Section E.2 the active components that were developed for the field test environment. By leveraging these new elements, new functionalities were realised and tested as described in Section E.3.

## E.1 Field Test Outline and Architecture

The area that was chosen for the field test consists of four primary substations and several feeders per substation. It was thus focused on the medium voltage level with a nominal voltage of 20 kV. Each of the primary substations contains two 63 kV to 20 kV transformers. Further details on the electrical parameters of the grid are given in Appendix A.4. From the substation *Roeschwoog* the feeder 15 was part of the test area, for *Preuschdorf* the feeders 11 and 10, for *Altenstadt* the feeders 25 and 16 and for *Lauterbourg* the feeders 14, 23 and 26. A simplified grid scheme that only considers the involved feeders is shown in Fig. E.1. This scheme does not show the configuration under normal operation, but under the specific field test configuration, bringing the open points to remotely controllable switches (RCS). This is possible as the topology of the grid offers some flexibility: it is operated radially but contains loops and meshes allowing configuration changes. On the scheme of Fig. E.1, no manual switches but only RCS - named “IPT” for **i**nterrupteur de **p**oste **t**éléconduit in French - are visualised. Only those are of importance for the use cases of the field test, especially the reconfiguration for the self-healing of the grid, see Chapter 10. The remotely controllable switches are normally associated with a remote terminal unit (RTU). A RTU is an electronic device containing a processor-unit that builds the interface between sensors and actors and a control system (classically the SCADA). For this purpose it can communicate with the control system to send and receive data.

The considered grid area contains five PV systems directly connected to the medium voltage grid. But only one was actively participating and controllable during the field test. Further on, two charging stations for electric vehicles were explicitly installed for the tests to allow the inclusion of controllable loads into the field test. The controllable PV system as well as the charging stations are connected to feeder 26 of *Lauterbourg*.

### E.1.1 Architecture of the Grid Operation

The architecture that is realised in the field test for the grid operation is a trade-off between the structure proposed in Chapter 7.2 and the physical devices available in the grid. Key actors are the *substation DSOs*, that are responsible for the grid operation in their respective *substation federation*. Details on the field test specific implementation of these components can be found in Section E.2.3. Instead of the *cell DSOs* introduced in Chapter 7.2, several *advanced RTUs* are used. These *advanced RTUs* provide quite similar functions as *cell DSOs*

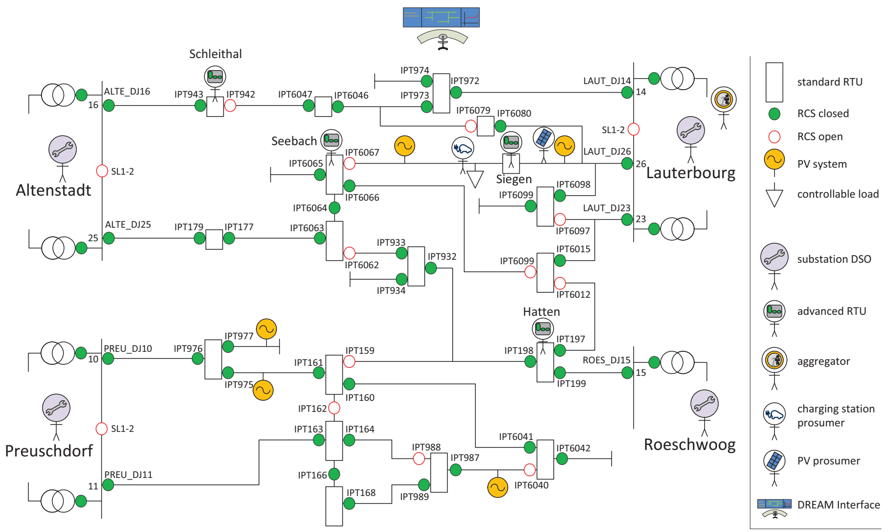



Figure E.1: Scheme of the field test grid area including the active components of the grid operation. The communication paths are omitted for visibility reasons.

but have with regard to the field test a different focus. Further details on *advanced RTUs* are described in Section E.2.2. To integrate the two prosumers into the grid operation, two different actors were developed, one for the PV system (*PV prosumer*) and one for the charging stations (*charging station prosumer*). These two prosumers are further described in Section E.2.4 and Section E.2.5. As the two prosumers are both connected to the *substation federation* of *Lauterbourg*, only there an *aggregator* is necessary. Further on, to allow the supervision of the testing process a user interface called *DREAM Interface* was set up. Its key capabilities are described in Section E.2.1.

## E.1.2 Communication Architecture

As motivated in Section D.1.3, the communication between the actors of the grid operation is realised with XMPP. The limitation of XMPP with regard to decentralisation is that is requires a communication server. As Section 11.2.1 describes it, this is is overcome by using local XMPP servers for each of the *substation federations*. This means most of the actors are connected to two communication servers, see Fig. E.2 for a focus on the field test scheme including the dotted "local" and dashed "global" communication possibilities. In the field test, some actors were placed behind the high-security fire wall of the control centre, e.g. the *DREAM Interface*. The *advanced RTUs* and *substation DSO* were placed in sub-networks realised as virtual private network on the field. And the the *charging station prosumer* and *PV prosumer* needed to be able to communicate with the public internet. The communication that was further required to combine the physical devices in the grid, with the software part is described more in detail for each of the active components in the following.

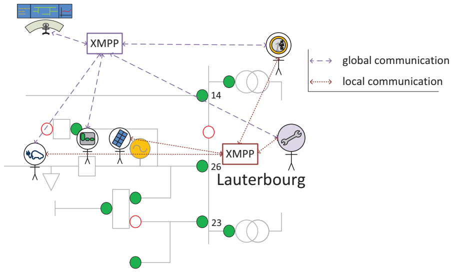



Figure E.2: Communication between the active components realised with XMPP, providing global and local communication.

### E.1.3 Compromises

The main challenge of the field test was to combine the existing centralised environment of the SCADA with the distributed new infrastructure of the new grid operation. This sometimes required trade-offs with regard to the distributed structure. The main guideline for design decisions in this case was to preserve the distributed way in which decisions are taken, also if this sometimes required central communication paths. Further on, the desired command of PV system and charging stations could not be realised with fully self-written software. To interact with the physical devices the help of commercial third parties was required. These commercial solutions were especially developed for the field test and comprised web services to provide the required functions.

To really place every actor on its own hardware, 12 computers would have been necessary. For the four *advanced RTUs* this was assured, as it was the aim to combine them with standard devices of the grid infrastructure. The *DREAM Interface* was hosted on a virtual machine on a server in the control centre. For the other actors, four workstation computers were set up for each of the four substation federations. These computers hosted the actors that were available in each of the federations. To still guarantee the complete separation between the actors, each of them was running on a particular virtual machine.

Especially in the debugging phase of the tests, it would have been time-consuming to physically place the four PCs at their geographic location in the primary substations in the field. To simplify the tests, they were connected to the sub-network that would also have been available in the geographic locations of the primary substations, but placed near the offices.

The control of a grid, especially the remote activation of switches, is a very sensible and critical issue as it might result in outages for the clients. Thus every action of the grid operation that might influence the grid, like the activation of flexibilities, needed to be validated by human action via the *DREAM Interface*. For switching actions, this visual output on the *DREAM Interface* was the only output realised by the grid operation. This was done as it was too risky for the DSO to give the direct control over the switches to non-standard software.

## E.2 Active Components

The development of the active components of the grid operation was the major task for the field test. Although the core behaviour did not change compared to the related actors in simulation, see Appendix D, the in- and output functions needed to be adjusted. In the following all the active components and their field test specific implementations are presented.

### E.2.1 DREAM Interface and Graphic User Interface

An important feature for the testing was a suitable interface that allowed the proper monitoring and control of the tests. This was the main function of the *DREAM* [1] *Interface*. Fig. E.3 gives a screenshot of the main window of the graphic user interface (GUI). During the test period,

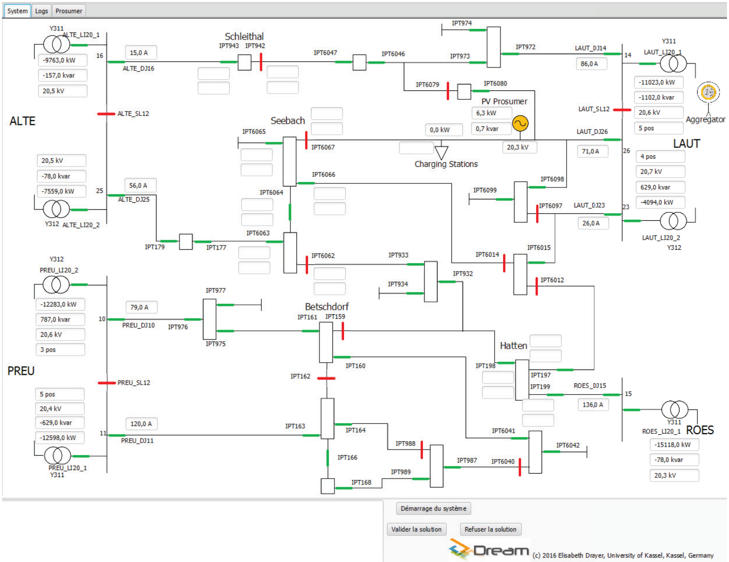



Figure E.3: Screenshot of the *DREAM Interface*. The values displayed represent the grid state at the 10.11.2016 around 10:30. The language is chosen to be French, as can be seen on the buttons of the interface.

this interface was running in parallel to the classic SCADA system in the control centre, see Fig. E.4. This GUI was developed using `JavaFX` [232]. As part of an international project

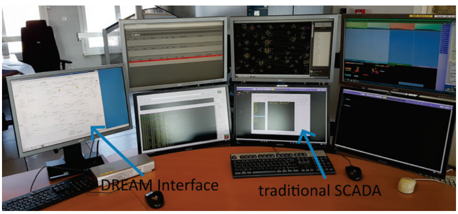



Figure E.4: *DREAM Interface* running in parallel to the classic SCADA system, source: J. Boeglin, Strasbourg Électricité Réseaux.

[1]For the project in which this was developed.

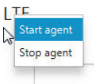
the GUI was developed in English. But for the daily use in a French control centre, it needed to be available in French. To allow the switching between different languages `Java resource bundles` were used. Thus, the code itself is independent of the languages, the language specific data is stored in a `.properties` file. The main functions of this GUI are:

- **Visualisation of measurements and grid status:** The visualisation and supervision of the actual grid state is an important function of the GUI. For this all available measurements are displayed and periodically updated. Also the grid status, that means the position of switches, is visualised and updated.

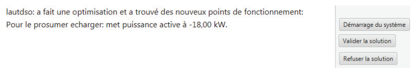
- **Management of running actors:** The code for all active components needs to be started in their particular virtual machine or on their particular device. This made them run in “standby” mode. They then can be activated for the grid operation directly from the GUI realised by context menus hidden behind each of the actors names, see Fig. E.5a.

- **Display and validation of solutions:** After an optimisation, the solution, that means the new set points, are not automatically transferred to the prosumers, but firstly displayed on a dedicated field within the GUI, see Fig. E.5b. The user can then validate this solution. For the reconfiguration this output is the only official solution in the field test, as a direct interaction with the RCS is too risky especially for the first runs. The solution (that means a suggestion of which switches to open and which to close) can then be followed by the operator.

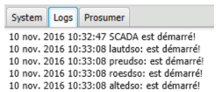
- **Log of actions:** To keep track of the behaviour of the actors of the grid operation they inform the interface about all actions they take. These logs are collected and displayed together with the name of the agent and a time stamp for verification and future analysis, see Fig. E.5c.




(a) Context menu for agent management.




(b) Solution field with validation buttons




(c) Log of agent actions.

Figure E.5: Functions provided by the GUI.

### E.2.2 Advanced RTU

One important aspect of the field test was to directly integrate the concepts and new functionalities in a common device of the power system. For this a very modern, but state-of-the-art remote terminal unit (RTU) was used in which the new functionalities were integrated. The RTU that was used for this purpose was the RTU Easergy T300 of Schneider Electric [233]. State-of-the-art RTUs can process measurements of the grid state available through connected sensors. They also “know” about the state of e.g. switches and fault passage indicators and can command them. This information is stored in the local data base of the RTU, here called “coreDB”. The RTU can transmit these measurements or receive control signals, e.g. for open or close commands via communication protocols like IEC 104. On the *advanced RTUs* an additional layer hosting the Java virtual machine has been integrated by the manufacturer of the

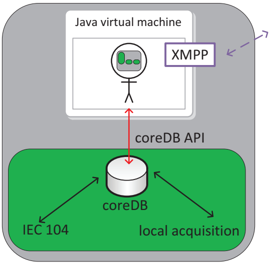



Figure E.6: Software layers of an *advanced RTU*, based on an initial picture of J. L. Garrote Molinero, Schneider Electric.

RTU, see Fig. E.6. In this Java virtual machine, the functionalities provided by the *advanced RTU* agent have been implemented, including the communication using XMPP. The measurements available in coreDB must be accessible from the Java layer. This is achieved using a coreDB API[2] that provides easy to use Java functions allowing the reading (e.g. measurements) and writing (e.g. switch control) of the data stored in coreDB [234].

### Controller-in-the-Loop Tests

RTUs that are installed in the power system are key devices and their proper functioning must be guaranteed. Therefore, the installation of the Java layer on the RTUs in the field was preceded and accompanied by extensive tests in a laboratory environment, see Fig. E.7 for a scheme. An *advanced RTU* is connected with a laboratory server. With this server the Java

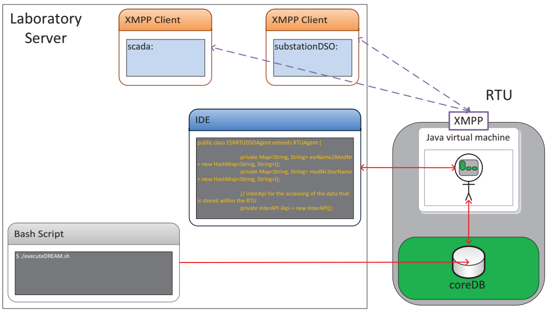



Figure E.7: Schema of the controller-in-the-loop test for the *advanced RTU*.

code is compiled and can be automatically transferred to the RTUs. By using an integrated development environment (IDE) the code on the RTU can be executed in debugging mode, so that every step can be monitored. Additionally, all types of measurements and switch states can be written into the coreDB of the RTUs by using a bash script. This pretends to be the actual environment of the RTU and allows the realistic validation of the new functions under all sorts of different grid states. To test the correct communication behaviour, XMPP clients that

[2]Application Programming Interface: defines the functions and expected results of software components; here the library to access values stored in coreDB from Java

pretend to be the communication parters of the *advanced RTU* are running on the laboratory server. So all messages received by them can be verified.

**Field Test**

The RTUs installed in the field are used to read from coreDB, mainly to take measurements (voltage and current) via sensors and to get the status of switches and FPIs. The measurements are analysed according to the traffic light approach described in Section 8.1. This happens periodically every two to 10 minutes. Changes in the status of switches or the activation of FPIs are treated on an event basis. The coreDB API triggers if either of them changes the status. This information is then sent to the *substation DSO*. Fig. E.8 contains a screenshot of a RTU in the field taking measurements. The writing from the Java layer into coreDB,

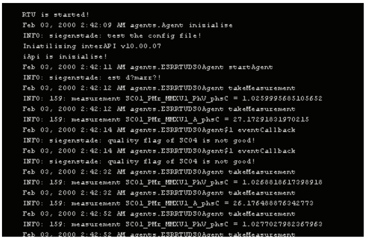



Figure E.8: Screenshot of running RTU in the field; the internal RTU time is not correctly set.

that means the command of switches, was not tested on a RTU that was part of the regular installations in the field but on a separate set-up: An *advanced RTU* was introduced into a low voltage circuit containing a light bulb (as visible control). On the measurement inputs of the *advanced RTU* a controllable voltage source was connected, so that different measurements could be realised for the RTU. Depending on the measurements the *advanced RTU* opens or closes the switch.

### E.2.3 Substation DSO

From a functionality standpoint, the *substation DSO* is the main player in the area of the *substation federation*. It is running the algorithms for the analysis of grid state according to the power system traffic light - Chapter 8.1, the heuristic optimisation - Section 9.1- and performs the self-healing in the case of permanent faults - Chapter 10. These functionalities were extensively tested and validated in simulations before introducing them into the field test environment, see the previous chapter. However, methods like the collection of measurements had to be developed specifically for the field test conditions. In a perfectly distributed grid operation, the devices running the code for the *substation DSO* would be directly placed at the premises of the primary substation. Or they would at least have direct access (via remote communication or locally) to the measurements and control parameters available through the substation equipment. But the sealed SCADA system of the field test environment made it impossible to access the measurements directly at the primary substation, at least without tremendous investment in additional equipment. With modern IT-components this information was only accessible from the SCADA data bases.

The structure given in Fig. E.9, was therefore developed, trying to keep the highest level of decentralised decision, although relying on a central server for the provision of measurements due to technical constraints in the field.

The four *substation DSOs* were hosted in four virtual machines. The available measurements of the primary substations are the current values for each of the feeders, the voltage magnitude both on the high and the medium voltage side of the transformers as well as the active and reactive power flows over the transformers. These measurements are refreshed every 10 minutes, thus setting the time interval of the field test to 10 min. The available status information includes the state of the circuit breaker, as well as the status of RCS and FPIs in the grid area powered by a particular *substation DSO*. This data is stored in the data base of the SCADA. From there it is periodically transferred to a web service. From this web service - provided by the French company REQUEA[3] - the *substation DSO* can fetch the dedicated measurements and status information.

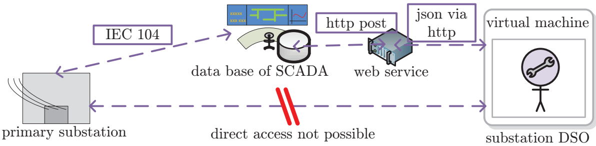



Figure E.9: Necessary data transfer path to provide the *substation DSOs* with their particular measurements.

## E.2.4 PV Prosumer

The PV system available for the field test has an installed power of 224 kW and covers the roof of an agricultural building. A picture of the building and the installed PV system can be found in Fig. E.10. This system consists of 19 inverters manufactured by Fronius[4]. 17 of these inverters have an apparent power of 12 kVA and two of 10 kVA. The PV system has its own secondary substation that connects it directly with the medium voltage grid.

Figure E.10: Picture of the PV system which was available for the field test, source: M. Gabel, Strasbourg Électricité Réseaux.

### Monitoring and Control

The monitoring and control of this system by the *PV prosumer* was realised by an intermediate web service developed in cooperation with REQUEA. This https web service translated

[3]www.requea.com
[4]www.fronius.com

the requests coming from the *PV prosumer* into inverter specific commands. This information was received by a local PC available on the premises of the PV system. This computer communicated with the inverters via Modbus. Measurements from the PV system take the same way back to the *PV prosumer*. Fig. E.11 visualises this communication path. To request measurements of the actual state of the PV system the *PV prosumer* uses the `GET`-request method proposed by http. The data is coded in json-Format [212]. With Jackson JSON Processor [213] this can be directly translated into Java objects. The data received by the *PV prosumer* contains a list of measurements for each of the inverters ranging from `resourceId1` (the first inverter) to `resourceId19`, the 19th inverter. For each inverter a list of measurements is available, see Table E.1 for the list of measurements available per inverter. Each measurement is combined with the date and time when the measurement was taken, coded in Unix time. As

Table E.1: List of available measurements per inverter.

| variable name | description | unit |
|---|---|---|
| `customId_Tension` | voltage | V |
| `customId_PA` | apparent power | VA |
| `customId_PR` | reactive power | var |
| `customId_PF` | power factor | without unit, but on a basis between 0 and 1000 |
| `customId_PF_Set` | imposed power factor | without unit, but on a basis between 0 and 1000 |

the *PV prosumer* represents not just one inverter but the whole PV system, it can calculate its actual active and reactive power set point by summing up the values given per inverter. Also, from a logic point of view the PV system is considered as directly connected to the medium voltage grid. But for the voltage, only the low voltage measurement of the inverters are given. To overcome this limitation, the known transformation ratio of the secondary substation is used to approximately calculate the voltage at the medium voltage side.

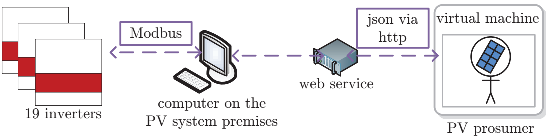



Figure E.11: Interaction between the *PV prosumer* and the PV system via an intermediate web service.

### Flexibility Provision and Imposing of new Set Point by the *PV Prosumer*

The flexibility this *PV prosumer* could propose for the optimisation of the *substation DSO*, was for the field test limited on reactive power. This had mainly legal and financial reasons. This flexibility was proposed as a list of possible reactive power values, in the range between $Q_{\min}$ to $Q_{\max}$. To fix a certain reactive power set point the power factor can be imposed on the inverters. They then try to reach the set value of the power factor. The technical possible power factors ranged from 1 to ±0.85, but it was necessary to chose the same power factor for all inverters. Relying on the current status of the PV system the list of possible reactive power set points is calculated by the *PV prosumer*. For this the admissible range of the power factor (1 to ±0.85) is divided into $n_{\text{pf}}$ slices, here 1000. For each of this intermediate power factors

$pf_i$ it is assumed that this power factor is applied on each of the inverters $j$ and the possible reactive power per inverter $j$ is calculated

$$Q_{i,j} = \sqrt{P_j^2 \cdot \left(\frac{1}{pf_i^2} - 1\right)}. \tag{E.1}$$

This value can not directly be assumed as a check must be performed if the inverter still respects the limits of its apparent power $S_j$

$$Q_{i,j} = \begin{cases} Q_{i,j} & \text{if } \sqrt{P_j^2 + Q_{i,j}^2} \leq S_j \\ Q_{\max,j} & \text{if } \sqrt{P_j^2 + Q_{i,j}^2} > S_j \text{ with } Q_{\max,j} = \sqrt{S_j^2 - P_j^2} \end{cases}. \tag{E.2}$$

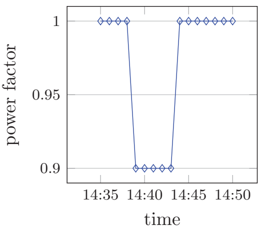
Then the sum is made over the reactive power of all inverters with this particular power factor

$$Q_{i,\text{ges}} = \sum_{j}^{n_{\text{inverter}}} Q_j\left(pf_i\right). \tag{E.3}$$

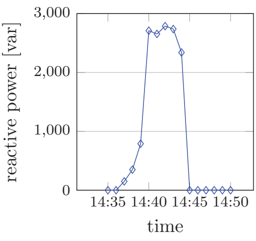
As result of the optimisation of the *DSO agent* or for the local control of the prosumer itself, the requested reactive power needs to be provided by the PV system. For this the *PV prosumer* keeps a map that combines a certain reactive power value with the required power factor. It thus can request this power factor. This is done by using the same web service as for the measurements.

### Function Test

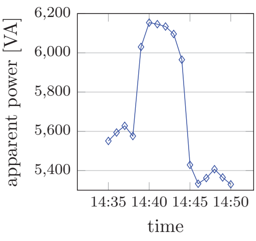
The graphs in Fig. E.12 show the behaviour of the first inverter while imposing a power factor of 0.9. The rise of the reactive power (Fig. E.12b) is very remarkable, as well as the increase of the total apparent power of the inverter (Fig. E.12c).




(a) Power factor $\cos\varphi$




(b) Resulting reactive power $Q$




(c) Apparent power $S$

Figure E.12: Function test of the *PV prosumer* exemplified with the behaviour of one inverter.

## E.2.5 Charging Station Prosumer

Two fast charging stations manufactured by Hager[5] were installed at the premisses of a secondary substation in the same village as the PV system. Each of the charging stations contained

[5] `www.hager.de/ladestationen-fuer-elektromobilitaet/ladestationen/ladestationen-privat-und-halboeffentlich/xev653c/923758.htm`

two charging points with maximal 22 kW power per plugged car. For the tests a maximum of four Renault Zoe from the car pool of the DSO were connected to the charging stations, see Fig. E.13.

Figure E.13: Two charging stations with four cars connected for charging, source: M. Gabel, Strasbourg Électricité Réseaux.

### Monitoring and Control

These charging stations were used as flexible loads. Together with Hager and the company Freshmile [6] the possibility to modulate the charging power between a maximal and minimal power was developed. The first step to allow this power modulation was a special firmware for the charging stations proposed by Hager as this functionality is not standard for charging stations. Based on this and by using the Open Charge Point Protocol [235] Freshmile set up a web service that builds the interface between the *charging station prosumer* and the physical charging stations, see Fig. E.14. The available measurement is the current charging power in

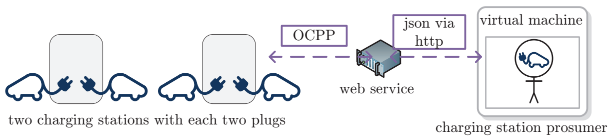



Figure E.14: Interaction between the *charging station prosumer* and the two charging stations via an intermediate web service.

kW. This is an aggregated value, combining the charging power of the two charging stations. Additionally, the maximal and minimal charging power is available through the web service. This depends on the number of cars that are charging in parallel and their charging status.

[6] www.freshmile.com

### Flexibility Provision and Imposing of new Set Point by the *Charging Station Prosumer*

Per default, the charging stations try to charge the cars with the maximal available power. By reducing the charging power, the charging station can provide flexibilities to the *DSO agent*. The list of possible flexibilities can then be created between the maximal and minimal charging power. A new charging power should not fall below the minimal charging power. Otherwise the car is completely separated from the charging station and the re-increase of the charging power is not possible. This is due to the interal charging station manufacturing standards. To impose a new set point at the charging station, the *charging station prosumer* uses a `Post`-request of the web service.

### Function Test

Fig. E.15 shows the modulation of the charging power after a new, reduced charging set point has been imposed. From imposing a new set point by the *charging station prosumer* to the physical modification of the charging power by the charging stations it takes roughly three minutes. As can be seen the new set point is only "roughly" attained. This is related to the complex interaction between cars and charging stations depending on the car model and the charging level of the batteries.

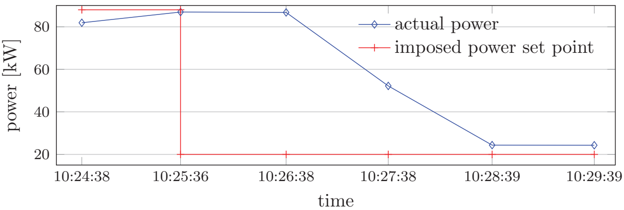



Figure E.15: Modulation of charging power (in blue) according to the imposed set point (in red).

## E.3 Test of New Functionalities

The active components developed in the section above were put together to realise new functionalities. Apart from an increased visibility because of the *DREAM Interface* the two main functionalities to be tested were the optimisation of the grid state - Section E.3.1 - and the self-healing Section E.3.2.

### E.3.1 Optimisation of Grid State

To test the optimisation in the field was challenging, as the considered grid area did not actually have any constraints with regard to the voltage profile or the loading of lines. To nevertheless test the optimisation, the admissible margins of voltage profile violations and the admissible operating current thresholds of lines were considerably reduced. The Fig. E.12 and Fig. E.15 result from two different test cases. The test case belonging to Fig. E.15 was an assumed congestion of the lines of feeder 26 of *Lauterbourg*. Fig. E.12 was the result of an overvoltage around the coupling point of the PV system.

### E.3.2 Reconfiguration for Self-Healing after Fault

The application of the self-healing method of Chapter 10 in the field test environment was strongly coordinated with the involved DSO. There were several constraints that needed to be considered when going from simulation to the field test environment. One was that failures can or must not be created “at wish” in the real grid. Also with a fully successful use of the self-healing approach, this would nevertheless compromise clients connected to the grid. A way to overcome this limitation was to set up the system and let it supervise the considered test area during several months. Unluckily for the tests, there was no permanent fault in this specific area during the considered months. To nevertheless test the approach in the field, the signals that would normally be generated by a fault were manually injected into the system. This was done in two ways, the first and easier way was to disconnect the web service that provides the interface between the SCADA data base and the *substation DSO* (see Fig. E.9) from the automatic updates. Then the data base was modified so that it contained the information it would have in case of a permanent fault at a certain position. The second, more complete way was done by using the equipment that is normally used when new devices are installed in the grid and the communication capabilities with the SCADA need to be tested. Thus, the signals were created locally, at the affected substation (by “overwriting” the signals sent to the SCADA) and at the FPIs (they have a “test” button where they can be activated manually). This required two technicians locally at the primary and secondary substations, one injecting the circuit breaker activation, the other activating the FPIs. The picture in Fig. E.16 shows this manual overwriting of circuit breaker signals.

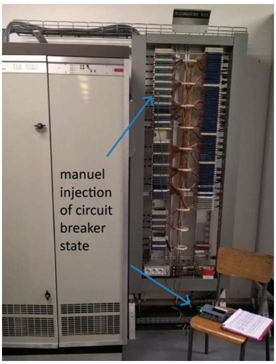



Figure E.16: Injection of circuit breaker activation signal, Source: S. Wernert, Strasbourg Électricité Réseaux.

Another constraint was, that the DSO naturally did not accept that the here presented approach could automatically open and close switches in the field. As described in Section E.2.1, this was overcome by proposing the solution in the form of a text output. This output is as close as possible to the actual switching order, so that the operator can simply follow line by line the instructions. This means: first the faulty *elementCell* must be isolated, by opening the boundary RCS. Then all required RCS are closed, and then all required RCS are opened. This process can temporarily create meshed structures, but interrupts the least number of clients.

### Consideration of Side Effects

In simulations, the trigger event starting the self-healing process is the opening of a circuit breaker at the feeder. In reality this feeder can be opened not only for protection purposes but also to voluntarily isolate the downstream feeder for maintenance reasons, or as an intermediate step in reconfiguring the grid. So each operation of the circuit breaker is tagged with a “cause” that further described the reason why it tripped. Only for reasons related to “protection” the opening of a circuit breaker actually could be used to trigger the self-healing.

There is another aspect that needs to be considered: Feeders with a high percentage of overhead lines, and thus the feeders that more likely suffer permanent faults, are generally equipped with an automatic reclosing equipment. This means when the circuit breaker trips, it does not stay open, but is reclosed (sometimes several times) after approx. 300 ms. The idea is that this eliminates most of the non-permanent faults like branches, that are simply burned away by the fault current. For feeders with extensive reclosing automation, this process can sometimes take up to 20 seconds. Depending on the communication between the SCADA and the circuit breaker, the information about the tripping might be sent before or after the reclosing definitely did not succeed. But sometimes the first reclosing cycle is so fast that the FPIs are not yet triggered, and so the identification of the faulty *elementCell* might be misled. To avoid all incoherent information, the self-healing tested here only starts after the end of the reclosing process.

Another aspect where direct application from simulation to the field test can create problems are high-resistive faults, mainly earth faults. As the fault current is too low, they do not activate the FPIs, and thus a high-resistive earth fault might look like a fault in the first *elementCell* of the feeder. Here the above mentioned “cause” is also used, as the trigger to open the circuit breaker for a high resistive fault is different to a normal short circuit.

### Example Result

Preliminarily to the tests in the field, the grid data was used to simulate the self-healing. The results of this simulation are described in Section 10.4.2. The here presented result comes from the testing in the field test environment as described above by manually injecting the information related to the fault. Fig. E.18 visualises the state of the grid directly after the fault. The circuit breaker `PREU_DJ11` is open, leading to a fully unsupplied feeder. The *substation DSO* supplying the grid area fed by the primary substation *Preuschdorf* is in charge of the self-healing process. It found a valid solution in the intra-reconfiguration step. The calculations took less than 3 seconds, while 31 possible solutions have been evaluated. The best solution, as it is visualised in Fig. E.19, is to isolate the faulty *elementCell* by opening `IPT163`. The circuit breaker `PREU_DJ11` is already open. The resupply is realised by closing `IPT162`. Fig. E.17 shows the solution in the output field of the *DREAM Interface*. The switching actions could then have been executed by the operators.

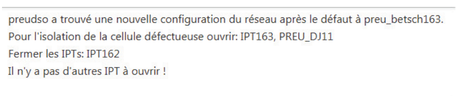

preudso a trouvé une nouvelle configuration du réseau après le défaut à preu_betsch163.
Pour l'isolation de la cellule défectueuse ouvrir: IPT163, PREU_DJ11
Fermer les IPTs: IPT162
Il n'y a pas d'autres IPT à ouvrir !

Figure E.17: Proposed solution output for the self-healing test case.

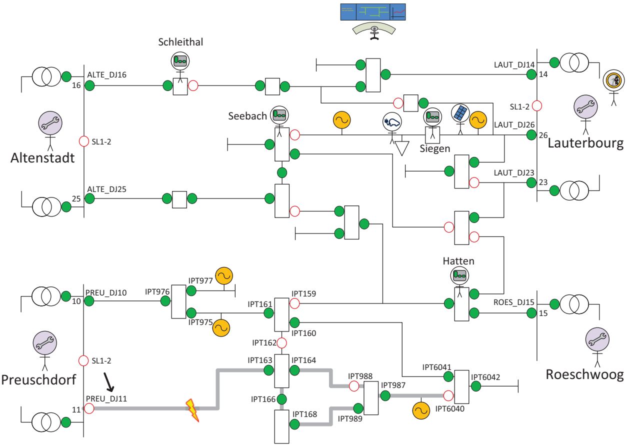



Figure E.18: Grid configuration before the self-healing with faulty *elementCell* and unsupplied feeder 11.

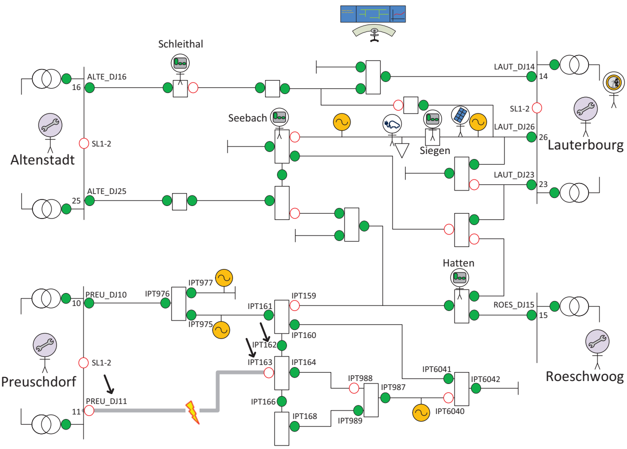



Figure E.19: Grid configuration after the self-healing. The faulty *elementCell* is isolated and the intact parts are resupplied.

# APPENDIX F

# UML Diagrams

This appendix gives a list of diagrams realised with the unified modelling language (UML). In software engineering, UML is the standard way to model relations between components and to visualise software properties. They are thus an important intermediate step in the development of complex software projects and help to give in-depth understanding without actually needing to read software code.

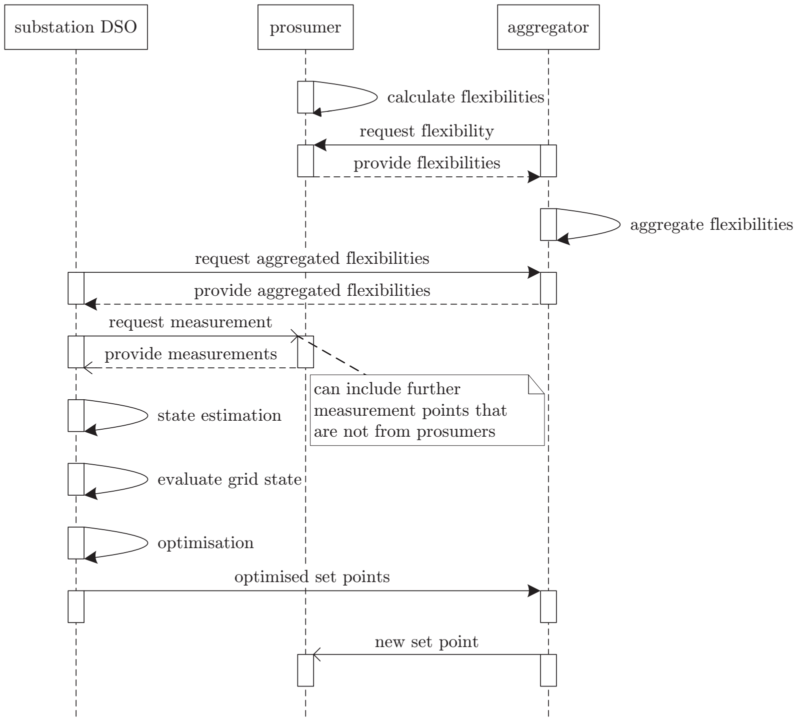



Figure F.1: UML sequence diagram for amber optimisation after voltage profile violation.

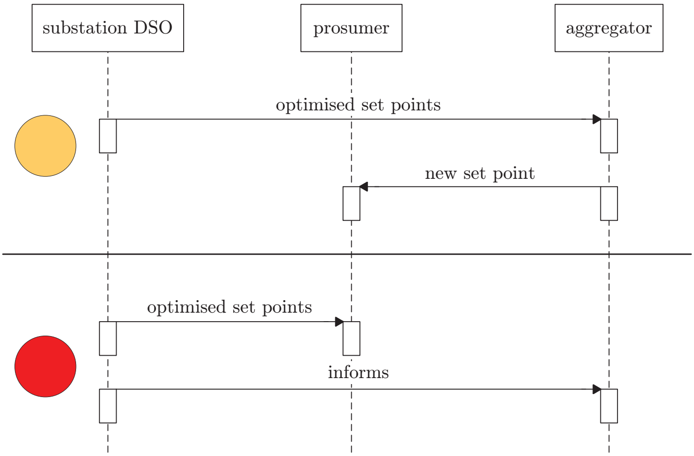



Figure F.2: UML sequence diagram for agent interaction when communicating the set point in amber or red phase.

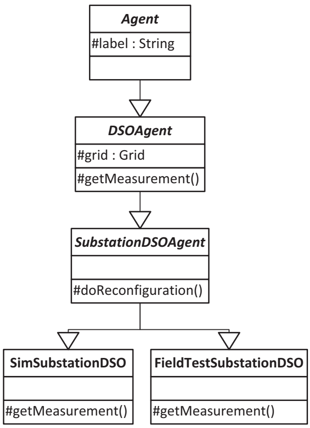



Figure F.3: UML class diagram for relationship between abstract superclasses and specific agent types.

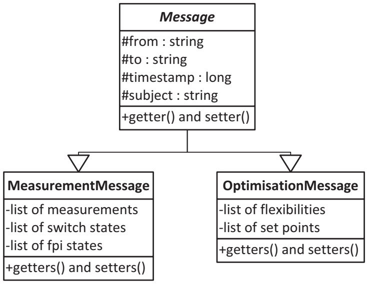



Figure F.4: UML class diagram for abstract general message class and subclasses for different cases.

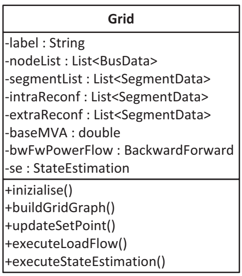



Figure F.5: UML class diagram for grid class with selection of attributes and methods.

APPENDIX G

# List of Acronyms

| | |
|---|---|
| ADMS | advanced distribution management system |
| DER | distributed energy resources |
| DG | distributed generator |
| DoS | denial of service |
| DSM | demand side management |
| DSO | distribution system operator |
| FPI | fault passage indicator |
| GUI | graphic user interface |
| HV | high voltage |
| ICT | information and communication technology |
| IEC | international electrotechnical commission |
| IED | intelligent electronic devices |
| IT | information technology |
| JSON | java script object notation |
| LV | low voltage |
| MAS | multi-agent system |
| MV | medium voltage |
| OLTC | on-load tap changer |
| OPF | optimal power flow |
| OSI model | open system interconnection model |
| PLC | power line communication |
| PSO | particle swarm optimisation |
| PV | photovoltaic |
| RCS | remotely controllable switch |
| RTU | remote terminal unit |

| | |
|---|---|
| SAIDI | system average interruption duration index |
| SAIFI | system average interruption frequency index |
| SCADA | supervisory control and data acquisition |
| SGAM | smart grid architecture model |
| TRL | technology readiness level |
| TSO | transmission system operator |
| UML | unified modelling language |
| XMPP | extensible messaging and presence protocol |

## APPENDIX H

# Publications

## H.1 Publications in Peer-Reviewed Journals

[D1] E. Drayer, N. Kechagia, J. Hegemann, M. Braun, M. Gabel, and R. Caire, “Distributed self-healing for distribution grids with evolving search space”, *IEEE Trans. Power Del.*, vol. 33, no. 4, pp. 1755–1764, Aug. 2018, see Chapter 10.

## H.2 Conference Proceedings

[D2] E. Drayer, J. Hegemann, M. Lazarus, and M. Braun, “Umsetzung des BDEW-Ampelkonzeptes für eine agenten-basierte Verteilnetzbetriebsführung”, in *ETG-Fachbericht - Von Smart Grids zu Smart Markets 2015*, VDE VERLAG GmbH, 2015.

[D3] E. Drayer, J. Hegemann, M. Lazarus, R. Caire, and M. Braun, “Agent-based distribution grid operation based on a traffic light concept”, in *23nd Int. Conf. on Electricity Distribution (CIRED)*, Lyon, 2015, see Chapter 8.

[D4] E. Drayer, F. Meyer, J. Hegemann, and M. Braun, “Control strategies for a decentralized, real-time operation of distribution grids”, in *IEEE PowerTech Eindhoven*, 2015, see Chapter 9.

[D5] R. Bärenfänger, E. Drayer, D. Daniluk, B. Otto, E. Vanet, R. Caire, T. Shamsi Abbas, and B. Lisanti, “Classifying flexibility types in smart electric distribution grids: A taxonomy”, in *CIRED Workshop 2016 Helsinki*, 2016.

[D6] E. Drayer, J. Hegemann, S. Gehler, and M. Braun, “Resilient distribution grids - cyber threat scenarios and test environment”, in *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2016, see Chapter 11.

[D7] E. Drayer, P. Pernigotto, J. L. Garrote Molinero, F. Ramos, M. Braun, and M. Lazarus, “From simulation to reality –Testing today a decentral grid operation of the future”, in *24th Int. Conf. on Electricity Distribution (CIRED)*, Glasgow, 2017, see Chater 12 and Appendix E.

## H.3 Invited Oral Presentations

[D8] E. Drayer, *Real time operation of distribution grids*, Public Final Event of the DREAM project, Dec. 2016.

[D9] E. Drayer, *Resiliente Netzbetriebsführung für das Verteilnetz - Die Kunst intelligent kaputt zu gehen*, "Life Needs Power" Energy Forum Hannover Messe, Apr. 2017.

[D10] E. Drayer, *Resiliente Netzbetriebsführung für das Verteilnetz - Die Kunst intelligent kaputt zu gehen*, 7. Workshop VDE/ITG-Fokusgruppe "Energieinformationsnetze und -Systeme", Apr. 2017.

[D11] E. Drayer, *Resiliente Netzbetriebsführung für das Verteilnetz - Die Kunst intelligent kaputt zu gehen*, DKE / VDE Innovation Campus, 2017.

[D12] E. Drayer, *Widerstandsfähige Betriebsführung für das Verteilnetz*, Jahresmittgliederversammlung VDE-Bezirksverein Kassel, Feb. 2017.

## H.4 Project Deliverables

[D13] R. Caire (ed.), *Dream reference object model and dictionary*, Deliverable D5.1 of the DREAM project, 2014.

[D14] E. Drayer *et al.*, *Solutions and practical implementations to enable distributed direct real time control at the distribution level*, Deliverable D4.2 of the DREAM project, 2015.

## H.5 Standards

[D15] I. Häring, M. Niedermeier, E. Drayer, and S. Müller, *Resilience analysis and improvement process in socio-technical systems*, New work item proposel for IEC, Aug. 2017.

## H.6 Supervised Theses

[D16] F. Meyer, "Entwicklung einer Matlab-Funktion zur lokalen statischen Spannungsregelung in agentenbasierten Verteilnetzen am Beispiel eines französischen Testnetzes", Master's thesis, University of Kassel, 2015.

[D17] M. Keita, "Bereitstellung der Blindleistung durch Photovoltaikanlage zur Spannunghaltung - ein Vergleich zwischen Deutschland und Frankreich", B.S. Thesis, University of Kassel, 2016.

# Bibliography


[1] *Energy 2020 - a strategy for competitive, sustainable and secure energy*, COM(2010) 639, European Commission, 2010.

[2] *Energy roadmap 2050*, COM(2011) 885, European Commission, 2011.

[3] *Directive 96/92/EC of the European Parliament and of the council of 19 December 1996 concerning common rules for the internal market in electricity*, Directive 96/92/EC, Official Journal of the European Communities, 1997.

[4] *Paris agreement*, FCCC/CP/2015/L.9, United Nations Framework Convention on Climate Change, 2015.

[5] *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung*, Bundesregierung Deutschland, 2010.

[6] *La loi no 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte*, Journal officiel de la République Française, 2016.

[7] *Directive 2009/28/EC of the European Parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*, 2009/28/EC, European Parliament and Council, 2009.

[8] *Gesetz zur Digitalisierung der Energiewende*, Bundesgesetzblatt, Gesetzesbeschluss des Deutschen Bundestages, 2016.

[9] *The digital energy systeme 4.0*, European Technology Platform SmtartGrids, 2016.

[10] *Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich*, Bundesgesetzblatt, Gesetzesbeschluss des Deutschen Bundestages, 2004.

[11] *Dreizehntes Gesetz zur Änderung des Atomgesetzes*, Bundesgesetzblatt, Gesetzesbeschluss des Deutschen Bundestages, 2011.

[12] V. Quaschning, *Regenerative Energiesysteme*. Hanser, 2013.

[13] S. Goel, Y. Hong, V. Papakonstantinou, and D. Kloza, *Smart grid security*. Springer, 2015.

[14] E. Smith, S. Corzine, D. Racey, P. Dunne, C. Hassett, and J. Weiss, “Going beyond cybersecurity compliance: What power and utility companies really need to consider”, *IEEE Power Energy Mag.*, vol. 14, no. 5, pp. 48–56, Sep. 2016.

[15] S. V. Buldyrev, R. Parshani, G. Paul, H. E. Stanley, and S. Havlin, “Catastrophic cascade of failures in interdependent networks”, *Nature*, vol. 464, no. 7291, pp. 1025–1028, 2010.

[16] *EEG in Zahlen 2015*, [Accessed: 01/09/2017], Bundesnetzagentur. [Online]. Available: `www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/zahlenunddaten-node.html`.

[17] *SmartGrids - Straegic Deployment Document for Europe’s Electric Networks of the Future*, European Technology Platform SmtartGrids, European Technology Platform, 2010.

[18] S. Massoud Amin and B. F. Wollenberg, “Toward a smart grid: Power delivery for the 21st century”, *IEEE Power Energy Mag.*, vol. 3, no. 5, pp. 34–41, Sep. 2005.

[19] H. Farhangi, “The path of the smart grid”, *IEEE Power Energy Mag.*, vol. 8, no. 1, pp. 18–28, Jan. 2010.

[20] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klockl, G. Andersson, and K. Frohlich, “Energy hubs for the future”, *IEEE Power Energy Mag.*, vol. 5, no. 1, pp. 24–30, Jan. 2007.

[21] T. Benz *et al.*, “VDE-Studie Der Zellulare Ansatz - Grundlage einer erfolgreichen, regionenübergreifenden Energiewende”, German, *VDE, ETG, Frankfurt a. M.*, 2015.

[22] Oxford Englisch Dictionary, *Resilience, n.* [Accessed: 18/05/2017], Oxford University Press. [Online]. Available: `www.oed.com/view/Entry/163619?redirectedFrom=resilience&`.

[23] J.-C. Laprie, “From dependability to resilience”, in *IEEE/IFIP Int. Conf. on Dependable Systems and Networks*, 2008.

[24] S. Hosseini, K. Barker, and J. E. Ramirez-Marquez, “A review of definitions and measures of system resilience”, *Reliability Engineering & System Safety*, vol. 145, pp. 47–61, 2016.

[25] C. S. Holling, “Resilience and stability of ecological systems”, *Annual Review of Ecology and Systematics*, vol. 4, no. 1, 1973.

[26] B. E. Biringer, E. D. Vugrin, and D. E. Warren, *Critical infrastructure system security and resilience*. CRC Press, 2013.

[27] *A framework for establishing critical infrastructure resilience goals - final report and recommendations by the council*, National Infrastructure Advisory Council, 2010.

[28] C. G. Rieger, D. I. Gertman, and M. A. McQueen, “Resilient control systems: Next generation design research”, in *2nd Conf. on Human System Interactions*, May 2009.

[29] G. A. Fink, R. L. Griswold, and Z. W. Beech, “Quantifying cyber-resilience against resource-exhaustion attacks”, in *7th Int. Symposium on Resilient Control Systems (ISRCS)*, Aug. 2014.

[30] “White Paper - Requirements for Secure Control and Telecommunication Systems”, BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., Oesterreichs E-Wirtschaft, Tech. Rep., 2015.

[31] C. Nan and G. Sansavini, “A quantitative method for assessing resilience of interdependent infrastructures”, *Reliability Engineering & System Safety*, vol. 157, pp. 35–53, 2017.

[32] M. Panteli and P. Mancarella, “The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience”, *IEEE Power Energy Mag.*, vol. 13, no. 3, May 2015.

[33] Z. Bie, Y. Lin, G. Li, and F. Li, “Battling the extreme: A study on the power system resilience”, *Proc. IEEE*, vol. PP, no. 99, pp. 1–14, 2017.

[34] M. Panteli, P. Mancarella, D. Trakas, E. Kyriakides, and N. Hatziargyriou, “Metrics and quantification of operational and infrastructure resilience in power systems”, *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4732–4742, Nov. 2017.

[35] Y. Wang, C. Chen, J. Wang, and R. Baldick, "Research on resilience of power systems under natural disasters - a review", *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1604–1613, Mar. 2016.

[36] J. Yan, Y. Tang, B. Tang, H. He, and Y. Sun, "Power grid resilience against false data injection attacks", in *IEEE Power and Energy Society General Meeting (PESGM)*, Jul. 2016.

[37] D. Kirschen and F. Bouffard, "Keeping the lights on and the information flowing", *IEEE Power Energy Mag.*, vol. 7, no. 1, pp. 50–60, Jan. 2009.

[38] acatech/Leopoldina/Akademienunion, *Das Energiesystem resilient gestalten*, Schriftenreihe zur wissenschaftsbasierten Politikberatung, 2017.

[39] A. J. Schwab, *Elektroenergiesysteme*. Springer, 2012.

[40] F. F. Wu, K. Moslehi, and A. Bose, "Power system control centers: Past, present, and future", *Proc. IEEE*, vol. 93, no. 11, pp. 1890–1908, Nov. 2005.

[41] T. Strasser, F. Andrén, J. Kathan, C. Cecati, C. Buccella, P. Siano, P. Leitão, G. Zhabelova, V. Vyatkin, P. Vrba, and V. Mařík, "A review of architectures and concepts for intelligence in future electric energy systems", *IEEE Trans. Industrial Electronics*, vol. 62, no. 4, pp. 2424–2438, Apr. 2015.

[42] J. Lunze, *Feedback control of large-scale systems*. Prentice Hall International, 1992.

[43] *International electrotechnical vocabulary*, IEC 60050-351-55, 2006. [Online]. Available: `www.electropedia.org`.

[44] R. Scattolini, "Architectures for distributed and hierarchical model predictive control - a review", *Journal of Process Control*, vol. 19, no. 5, pp. 723–731, 2009.

[45] J. Dunekl, A. Eberhart, S. Fischer, C. Kleiner, and A. Koschel, *Systemarchitekturen für Verteilte Anwendungen*. Hanser, 2008.

[46] G. Coulouris, J. Dollimore, T. Kindberg, and G. Blair, *Distributed systems - concepts and design*. Pearson, 2012.

[47] J. Ferber, *Multi-agent systems - an introduction to distributed artifical intelligence*. Addison-Wesley, 1999.

[48] V. Catterson, E. Davidson, and S. McArthur, "Embedded intelligence for electrical network operation and control", *IEEE Intell. Syst.*, vol. 26, no. 2, pp. 38–45, Mar. 2011.

[49] P. Vrba, V. Marik, P. Siano, P. Leitao, G. Zhabelova, V. Vyatkin, and T. Strasser, "A review of agent and service-oriented concepts applied to intelligent energy systems", *IEEE Trans. Industrial Informatics*, vol. 10, no. 3, pp. 1890–1903, Aug. 2014.

[50] M. Wooldridge, *An introduction to multiagent systems*. John Wiley & Sons, Ltd, 2006.

[51] S. D. J. McArthur, E. M. Davidson, V. M. Catterson, A. L. Dimeas, N. D. Hatziargyriou, F. Ponci, and T. Funabashi, "Multi-agent systems for power engineering applications - Part I: Concepts, approaches, and technical challenges", *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1743–1752, Nov. 2007.

[52] M. Wooldridge and N. R. Jennings, "Intelligent agents: Theory and practice", *The knowledge engineering review*, vol. 10, no. 02, pp. 115–152, 1995.

[53] S. Franklin and A. Graesser, "Is it an agent, or just a program?: A taxonomy for autonomous agents", in *Int. Workshop on Agent Theories, Architectures, and Languages*, Springer, 1996, pp. 21–35.

[54] A. L. Dimeas and N. D. Hatziargyriou, “Operation of a multiagent system for microgrid control”, *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.

[55] S. D. J. McArthur, E. M. Davidson, V. M. Catterson, A. L. Dimeas, N. D. Hatziargyriou, F. Ponci, and T. Funabashi, “Multi-agent systems for power engineering applications - Part II: Technologies, standards, and tools for building multi-agent systems”, *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1753–1759, Nov. 2007.

[56] K. Kok, “Multi-agent coordination in the electricity grid, from concept towards market introduction”, in *9th Int. Conf. on Autonomous Agents and Multiagent Systems: Industry track*, International Foundation for Autonomous Agents and Multiagent Systems, 2010, pp. 1681–1688.

[57] P. Leitão, S. Karnouskos, L. Ribeiro, J. Lee, T. Strasser, and A. W. Colombo, “Smart agents in industrial cyber-physical systems”, *Proc. IEEE*, vol. 104, no. 5, pp. 1086–1101, May 2016.

[58] S. K. Khaitan and J. D. McCalley, “Design techniques and applications of cyberphysical systems: A survey”, *IEEE Syst. J.*, vol. 9, no. 2, pp. 350–365, Jun. 2015.

[59] *Information technology – open systems interconnection – basic reference model: The basic model*, ISO/IEC 7498-1, 1994.

[60] J. F. Kurose and K. W. Ross, *Computer networking - a top-down approach*. Pearson, 2013.

[61] P. Baran, “On distributed communications networks”, *IEEE Trans. Communications Syst.*, vol. 12, no. 1, pp. 1–9, Mar. 1964.

[62] M. Metzger, *Wie können intelligente Software-Agenten helfen, erneuerbare Energien ins Netz zu integrieren?*, Siemens, 2012.

[63] Siemens, *DEMS - Decentralized energy management system*, 2014.

[64] ABB, *Distribution grid automation raising the bar in grid efficiency and reliability*, 2014.

[65] Schneider Electric, *The advanced distribution management system (ADMS)*, 2012.

[66] Y. Chollot, R. Coccioni, and L. Guise, *Transitioning to smart MV/LV substations as the cornerstone of your smart grid*, Schneider Electric, 2015.

[67] SAG GmbH, *iNES - Intelligentes Verteilnetz-Management*, 2013.

[68] BTC, *GRID Agent Netzregler*, 2015.

[69] Union of the Electricity Industry, *Flexibility and aggregration - requirements for their interaction in the market*, 2014.

[70] ETG- Task Force Regio Flex, “Regionale Flexibilitätsmärkte”, VDE-Studie, Tech. Rep., 2014.

[71] K. Knezović, M. Marinelli, P. Codani, and Y. Perez, “Distribution grid services and flexibility provision by electric vehicles: A review of options”, in *50th Int. Universities Power Engineering Conference (UPEC)*, Sep. 2015.

[72] F. Olivier, P. Aristidou, D. Ernst, and T. van Cutsem, “Active management of low-voltage networks for mitigating overvoltages due to photovoltaic units”, *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 926–936, Mar. 2016.

[73] P. Jahangiri and D. C. Aliprantis, “Distributed Volt/Var control by PV inverters”, *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3429–3439, Aug. 2013.

[74] P. N. Vovos, A. E. Kiprakis, A. R. Wallace, and G. P. Harrison, "Centralized and distributed voltage control: Impact on distributed generation penetration", *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 476–483, Feb. 2007.

[75] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, "Local reactive power control methods for overvoltage prevention of distributed solar inverters in low-voltage grids", *IEEE Journal of Photovoltaics*, vol. 1, no. 2, pp. 174–182, Oct. 2011.

[76] J. von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel, "Time in the sun: The challenge of high PV penetration in the German electric grid", *IEEE Power Energy Mag.*, vol. 11, no. 2, pp. 55–64, Mar. 2013.

[77] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, and N. D. Hatziargyriou, "Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research", *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2999–3008, Nov. 2017.

[78] Q. Li, F. Chen, M. Chen, J. M. Guerrero, and D. Abbott, "Agent-based decentralized control method for islanded microgrids", *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 637–649, Mar. 2016.

[79] H. E. Farag, E. F. El-Saadany, and R. Seethapathy, "A two ways communication-based distributed control for voltage regulation in smart distribution feeders", *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 271–281, Mar. 2012.

[80] K. Worthmann, C. M. Kellett, P. Braun, L. Grüne, and S. R. Weller, "Distributed and decentralized control of residential energy systems incorporating battery storage", *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1914–1923, Jul. 2015.

[81] C. Oerter and N. Neusel-Lange, "LV-grid automation system - A technology review", in *IEEE Power and Energy Society General Meeting*, Jul. 2014.

[82] G. Rohbogner, U. J. J. Hahnel, P. Benoit, and S. Fey, "Multi-agent systems' asset for smart grid applications", *Computer Science and Information Systems*, vol. 10, no. 4, pp. 1799–1822, 2013.

[83] T. M. Aljohani and M. J. Beshir, "Distribution system reliability analysis for smart grid applications", *Smart Grid and Renewable Energy*, vol. 8, no. 7, 2017.

[84] T. Stetz, "Autonomous voltage control strategies in distribution grids with photovoltaic systems - technical and economical assessment", PhD thesis, University of Kassel, 2013.

[85] *Smart grid reference architecture*, CEN-CENELEC-ETSI Smart Grid Coordination Group, Nov. 2012.

[86] M. Arnold, H. Rui, and W. H. Wellssow, "An approach to smart grid metrics", in *2nd IEEE PES Int. Conf. and Exhibition on Innovative Smart Grid Technologies*, Dec. 2011.

[87] J. Engels, H. Almasalma, and G. Deconinck, "A distributed gossip-based voltage control algorithm for peer-to-peer microgrids", in *IEEE Int. Conf. on Smart Grid Communications (SmartGridComm)*, Nov. 2016, pp. 370–375.

[88] C. Dou, D. Yue, Q. L. Han, and J. M. Guerrero, "Multi-agent system-based event-triggered hybrid control scheme for energy internet", *IEEE Access*, vol. 5, pp. 3263–3272, 2017.

[89] Q. Shafiee, J. C. Vasquez, and J. M. Guerrero, "Distributed secondary control for islanded microgrids - a networked control systems approach", in *38th Annual Conf. on IEEE Industrial Electronics Society*, Oct. 2012, pp. 5637–5642.

[90] J. A. Momoh, R. Adapa, and M. E. El-Hawary, "A review of selected optimal power flow literature to 1993. I. Nonlinear and quadratic programming approaches", *IEEE Trans. Power Syst.*, vol. 14, no. 1, pp. 96–104, Feb. 1999.

[91] J. A. Momoh, M. E. El-Hawary, and R. Adapa, "A review of selected optimal power flow literature to 1993. II. Newton, linear programming and interior point methods", *IEEE Trans. Power Syst.*, vol. 14, no. 1, pp. 105–111, Feb. 1999.

[92] B. Zhao, C. X. Guo, and Y. J. Cao, "A multiagent-based particle swarm optimization approach for optimal reactive power dispatch", *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 1070–1078, May 2005.

[93] F. Bellifemine, A. Poggi, and G. Rimassa, "Developing multi-agent systems with a fipa-compliant agent framework", *Softw. Pract. Exper.*, vol. 31, no. 2, pp. 103–128, 2001.

[94] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid technologies: Communication technologies and standards", *IEEE Trans. Industrial Informatics*, vol. 7, no. 4, pp. 529–539, Nov. 2011.

[95] I. Häring, G. Sansavini, E. Bellini, N. Martyn, T. Kovalenko, M. Kitsak, G. Vogelbacher, K. Ross, U. Bergerhausen, K. Barker, and I. Linkov, *Resilience and risk*. Springer, 2017.

[96] *Functional safety of electrical/electronic/programmable electronic safety-related systems*, IEC, 2010.

[97] A. Shostack, *Threat modeling: Designing for security*. Wiley, 2014.

[98] Fraunhofer IEEE and University of Kassel, *Pandapower*, [Accessed: 08/03/2018]. [Online]. Available: `https://pandapower.readthedocs.io/en/v1.4.3/index.html`.

[99] E. Vanet, "Distributed intelligence and heterarchical approach of distributed balancing markets in smart grids", PhD thesis, Communauté Université Grenoble Alpes, 2016.

[100] M. Khattabi, A. Kießling, and J. Ringelstein, "A novel agent based system architecture for smart grids including market and grid aspects", in *IEEE Power and Energy Society General Meeting*, Jul. 2011.

[101] T. Wagner, "Impact of remote controlled switches on distribution grid recovering processes", Master's thesis, KTH-School of Electrical Engineering, 2010.

[102] L. Le-Thanh *et al.*, *Guidelines for practical algorithm implementation*, Deliverable D2.2 of the INTEGRAL project, 2008.

[103] S. D. J. McArthur, P. C. Taylor, G. W. Ault, J. E. King, D. Athanasiadis, V. D. Alimisis, and M. Czaplewski, "The autonomic power system - network operation and control beyond smart grids", in *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Oct. 2012.

[104] L. Martini, H. Brunner, E. Rodiguez, C. Caerts, T. I. Strasser, and G. M. Burt, "The grid of the future and the need for a decentralised control architecture: The web-of-cells concept", in *24th Int. Conf. on Electricity Distribution CIRED*, 2017.

[105] A. Abur and A. G. Expósito, *Power system state estimation theory and implementation*. CRC Press, 2004.

[106] J. Chen, Y. Dong, and H. Zhang, "Distribution system state estimation: A survey of some relevant work", in *35th Chinese Control Conference (CCC)*, Jul. 2016, pp. 9985–9989.

[107] J.-H. Menke, J. Hegemann, S. Gehler, and M. Braun, "Heuristic monitoring method for sparsely measured distribution grids", *Int. Journal of Electrical Power & Energy Systems*, vol. 95C, pp. 146–155, 2018.

[108] K. Windt and M. Hülsmann, *Understanding autonomous cooperation & control - The impact of autonomy on management, information, communication, and material flow.* Springer, 2007.

[109] Y. Chistyakov, E. Kholodova, K. Netreba, A. Szabo, and M. Metzger, "Combined central and local control of reactive power in electrical grids with distributed generation", in *IEEE Int. Energy Conf. and Exhibition (ENERGYCON)*, Sep. 2012, pp. 325–330.

[110] B. Stott, O. Alsac, and A. J. Monticelli, "Security analysis and optimization", *Proc. IEEE*, vol. 75, no. 12, pp. 1623–1644, Dec. 1987.

[111] *BDEW-Roadmap - Realistic Steps for the Implementation of Smart Grids in Germany*, BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. 2013.

[112] *Voltage characteristics of electricity supplied by public distribution systems*, EN 50160, 1999.

[113] A. G. Bakirtzis, P. N. Biskas, C. E. Zoumas, and V. Petridis, "Optimal power flow by enhanced genetic algorithm", *IEEE Trans. Power Syst.*, vol. 17, no. 2, pp. 229–236, May 2002.

[114] T. Sousa, J. Soares, Z. A. Vale, H. Morais, and P. Faria, "Simulated annealing metaheuristic to solve the optimal power flow", in *IEEE Power and Energy Society General Meeting*, Jul. 2011.

[115] T. Niknam, M. R. Narimani, J. Aghaei, and R. Azizipanah-Abarghooee, "Improved particle swarm optimisation for multi-objective optimal power flow considering the cost, loss, emission and voltage stability index", *IET Generation, Transmission Distribution*, vol. 6, no. 6, pp. 515–527, Jun. 2012.

[116] J. Gunda, S. Djokic, R. Langella, and A. Testa, "Comparison of conventional and metaheuristic methods for security-constrained OPF analysis", in *AEIT Int. Annual Conference*, Oct. 2015.

[117] D. I. Koukoula and N. D. Hatziargyriou, "Gossip algorithms for decentralized congestion management of distribution grids", *IEEE Trans. Sustainable Energy*, vol. 7, no. 3, pp. 1071–1080, Jul. 2016.

[118] W. Zhang, W. Liu, X. Wang, L. Liu, and F. Ferrese, "Distributed multiple agent system based online optimal reactive power control for smart grids", *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2421–2431, Sep. 2014.

[119] J. Kennedy and R. Eberhart, "Particle swarm optimization", *IEEE Int. Conf. on Neural Networks*, vol. 4, pp. 1942–1948, 1995.

[120] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory", *6th Int. Symposium on Micro Machine and Human Science*, pp. 39–43, 1995.

[121] M. R. AlRashidi and M. E. El-Hawary, "A survey of particle swarm optimization applications in electric power systems", *IEEE Trans. Evolutionary Computation*, vol. 13, no. 4, pp. 913–918, Aug. 2009.

[122] K. Diwold, W. Yan, L. D. A. Garcia, L. Mocnik, and M. Braun, "Coordinated voltage-control in distribution systems under uncertainty", *47th Int. Universities Power Engineering Conf. (UPEC)*, 2012.

[123] S. Chen, W. Hu, C. Su, X. Zhang, and Z. Chen, "Optimal reactive power and voltage control in distribution networks with distributed generators by fuzzy adaptive hybrid particle swarm optimisation method", *IET Generation, Transmission Distribution*, vol. 9, no. 11, pp. 1096–1103, 2015.

[124] C. Diehl, "Entwicklung einer agentenbasierten Simulation zur Leistungsregelung im Smart Grid mithilfe von Optimierungen", Master's thesis, Technischen Hochschule Mittelhessen, 2013.

[125] M. Clerc, *Particle swarm optimization*. ISTE, 2006.

[126] K. E. Parsopoulos and M. N. Vrahatis, "Particle swarm optimization method in multiobjective problems", in *2002 ACM symposium on Applied computing*, ACM, 2002, pp. 603–607.

[127] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education", *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 12–19, Feb. 2011.

[128] L. Thurner, A. Scheidler, F. Schafer, J. H. Menke, J. Dollichon, F. Meier, S. Meinecke, and M. Braun, "Pandapower - an open source python tool for convenient modeling, analysis and optimization of electric power systems", *IEEE Trans. Power Syst.*, 2018.

[129] P. Kotsampopoulos, N. Hatziargyriou, B. Bletterie, and G. Lauss, "Review, analysis and recommendations on recent guidelines for the provision of ancillary services by distributed generation", in *IEEE Int. Workshop on Inteligent Energy Systems (IWIES)*, Nov. 2013, pp. 185–190.

[130] VDE-Anwendungsregel 4105, *Erzeugungsanlagen am Niederspannungsnetz - Technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz*, Aug. 2011.

[131] BDEW-Mittelspannungsrichtlinie, *Technische Richtlinie Erzeugungsanlagen am Mittelspannungsnetz*, Jun. 2008.

[132] F. Andrén, B. Bletterie, S. Kadam, P. Kotsampopoulos, and C. Bucher, "On the stability of local voltage control in distribution networks with a high penetration of inverter-based generation", *IEEE Trans. Industrial Electronics*, vol. 62, no. 4, pp. 2519–2529, Apr. 2015.

[133] T. Stetz, J.-C. Töbermann, M. Kraiczy, J. von Appen, M. Braun, J. Brantl, S. Schmidt, A. U. Schmiegel, D. Premm, S. Bröscher, and A. Jung, "Zusatznutzen von Photovoltaik-Wechselrichtern mit kombinierter Q (U)/P (U)-Regelung in der Niederspannung", in *Symposium Photovoltaische Solarenergie, Bad Staffelstein*, 2014.

[134] J. H. Braslavsky, J. K. Ward, and L. Collins, "A stability vulnerability in the interaction between volt-var and volt-watt response functions for smart inverters", in *IEEE Conf. on Control Applications (CCA)*, Sep. 2015, pp. 733–738.

[135] *Arrêté du 24 décembre 2007 pris en application du décret n° 2007-1826 du 24 décembre 2007*, French, [Accessed: 29/08/2017], République Française, 2007. [Online]. Available: `www.legifrance.gouv.fr/eli/arrete/2007/12/24/DEVE0772580A/jo/texte`.

[136] Bundesnetzagentur, *Allgemeinverfügung nach §52 S.5 EnWG zu Vorgaben zur formellen Gestalltung des Berichtes nach §52 S. 1 EnWG*, German, 2006.

[137] *Recommended practice for monitoring electric power quality*, IEEE 1159, 2009.

[138] F. B. Enacheanu, “Outils d’aide à la conduite pour les opérateurs des réseaux de distribution”, PhD thesis, Institut National Polytechnique de Grenoble, 2007.

[139] A. Abur, “A modified linear programming method for distribution system reconfiguration”, *Int. Journal of Electrical Power & Energy Systems*, vol. 18, no. 7, pp. 469–474, 1996.

[140] L. S. M. Guedes, A. C. Lisboa, D. A. G. Vieira, and R. R. Saldanha, “A multiobjective heuristic for reconfiguration of the electrical radial network”, *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 311–319, Jan. 2013.

[141] S. Civanlar, J. Grainger, H. Yin, and S. Lee, “Distribution feeder reconfiguration for loss reduction”, *IEEE Trans. Power Del.*, vol. 3, no. 3, pp. 1217–1223, Jul. 1988.

[142] A. Merlin and H. Back, “Search for a minimal-loss operating spanning tree configuration in an urban power distribution system”, in *5th Power System Computation Conf.*, 1975.

[143] M. Baran and F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing”, *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1401–1407, Apr. 1989.

[144] D. Shirmohammadi and H. W. Hong, “Reconfiguration of electric distribution networks for resistive line losses reduction”, *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1492–1498, Apr. 1989.

[145] S. K. Goswami and S. K. Basu, “A new algorithm for the reconfiguration of distribution feeders for loss minimization”, *IEEE Trans. Power Del.*, vol. 7, no. 3, pp. 1484–1491, Jul. 1992.

[146] K. Aoki, K. Nara, M. Itoh, T. Satoh, and H. Kuwabara, “A new algorithm for service restoration in distribution systems”, *IEEE Trans. Power Del.*, vol. 4, no. 3, pp. 1832–1839, Jul. 1989.

[147] A. L. Morelato and A. J. Monticelli, “Heuristic search approach to distribution system restoration”, *IEEE Trans. Power Del.*, vol. 4, no. 4, pp. 2235–2241, Oct. 1989.

[148] K. Aoki, T. Ichimori, and M. Kanezashi, “Normal state optimal load allocation in distribution systems”, *IEEE Trans. Power Del.*, vol. 2, no. 1, pp. 147–155, Jan. 1987.

[149] C. C. Liu, S. J. Lee, and S. S. Venkata, “An expert system operational aid for restoration and loss reduction of distribution systems”, *IEEE Trans. Power Syst.*, vol. 3, no. 2, pp. 619–626, May 1988.

[150] T. Taylor and D. Lubkeman, “Implementation of heuristic search strategies for distribution feeder reconfiguration”, *IEEE Trans. Power Del.*, vol. 5, no. 1, pp. 239–246, Jan. 1990.

[151] T. P. Wagner, A. Y. Chikhani, and R. Hackam, “Feeder reconfiguration for loss reduction: An application of distribution automation”, *IEEE Trans. Power Del.*, vol. 6, no. 4, pp. 1922–1933, Oct. 1991.

[152] S. Toune, H. Fudo, T. Genji, Y. Fukuyama, and Y. Nakanishi, “Comparative study of modern heuristic algorithms to service restoration in distribution systems”, *IEEE Trans. Power Del.*, vol. 17, no. 1, pp. 173–181, Jan. 2002.

[153] H. D. Chiang and R. Jean-Jumeau, “Optimal network reconfigurations in distribution systems. I. A new formulation and a solution methodology”, *IEEE Trans. Power Del.*, vol. 5, no. 4, pp. 1902–1909, Oct. 1990.

[154] H. D. Chiang and R. Jean-Jumeau, “Optimal network reconfigurations in distribution systems. II. Solution algorithms and numerical results”, *IEEE Trans. Power Del.*, vol. 5, no. 3, pp. 1568–1574, Jul. 1990.

[155] K. Nara, A. Shiose, M. Kitagawa, and T. Ishihara, “Implementation of genetic algorithm for distribution systems loss minimum re-configuration”, *IEEE Trans. Power Syst.*, vol. 7, no. 3, pp. 1044–1051, Aug. 1992.

[156] N. G. Bretas, A. C. B. Delbem, and A. de Carvalho, “Optimal energy restoration for general distribution systems by genetic algorithms”, in *Proc. Int. Conf. Power Syst. Technology*, Aug. 1998.

[157] J. Mendoza, R. Lopez, D. Morales, E. Lopez, P. Dessante, and R. Moraga, “Minimal loss reconfiguration using genetic algorithms with restricted population and addressed operators: Real application”, *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 948–954, May 2006.

[158] B. Enacheanu, B. Raison, R. Caire, O. Devaux, W. Bienia, and N. Hadjsaid, “Radial network reconfiguration using genetic algorithm based on the matroid theory”, *IEEE Trans. Power Syst.*, vol. 23, no. 1, pp. 186–195, Feb. 2008.

[159] L. W. Oliveira *et al.*, “Optimal restoration of power distribution system through particle swarm optimization”, in *IEEE PowerTech Eindhoven*, Jun. 2015.

[160] G. Lambert-Torres *et al.*, “Comparison between PSO and GA in system restoration solution”, in *Int. Conf. in Intelligent System Applications to Power Systems*, Nov. 2009.

[161] F. Ding and K. A. Loparo, “Hierarchical decentralized network reconfiguration for smart distribution systems - Part I: Problem formulation and algorithm development”, *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 734–743, Mar. 2015.

[162] D. Das, “A fuzzy multiobjective approach for network reconfiguration of distribution systems”, *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 202–209, Jan. 2006.

[163] A. M. Tahboub, V. R. Pandi, and H. H. Zeineldin, “Distribution system reconfiguration for annual energy loss reduction considering variable distributed generation profiles”, *IEEE Trans. Power Del.*, vol. 30, no. 4, pp. 1677–1685, Aug. 2015.

[164] A. Shapovalov, C. Spieker, C. Rehtanz, and T. Engelmeyer, “Forecast-based network reconfiguration algorithm”, in *Power Systems Computation Conference*, Aug. 2014.

[165] P. C. Ramaswamy, J. Tant, J. R. Pillai, and G. Deconinck, “Novel methodology for optimal reconfiguration of distribution networks with distributed energy resources”, *Electric Power Systems Research*, vol. 127, pp. 165–176, 2015.

[166] R. S. Rao, K. Ravindra, K. Satish, and S. V. L. Narasimham, “Power loss minimization in distribution system using network reconfiguration in the presence of distributed generation”, *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 317–325, Feb. 2013.

[167] R. Rajaram, K. S. Kumar, and N. Rajasekar, “Power system reconfiguration in a radial distribution network for reducing losses and to improve voltage profile using modified plant growth simulation algorithm with distributed generation (DG)”, *Energy Reports*, vol. 1, pp. 116–122, 2015.

[168] T. Nagata and H. Sasaki, “A multi-agent approach to power system restoration”, *IEEE Trans. Power Syst.*, vol. 17, no. 2, pp. 457–462, May 2002.

[169] J. M. Solanki, S. Khushalani, and N. N. Schulz, “A multi-agent solution to distribution systems restoration”, *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1026–1034, Aug. 2007.

[170] F. Ding and K. A. Loparo, “Hierarchical decentralized network reconfiguration for smart distribution systems - Part II: Applications to test systems”, *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 744–752, Mar. 2015.

[171] M. J. Ghorbani, M. A. Choudhry, and A. Feliachi, “A multiagent design for power distribution systems automation”, *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 329–339, Jan. 2016.

[172] A. Zidan, M. Khairalla, A. M. Abdrabou, T. Khalifa, K. Shaban, A. Abdrabou, R. El Shatshat, and A. M. Gaouda, “Fault detection, isolation, and service restoration in distribution systems: State-of-the-art and future trends”, *IEEE Trans. Smart Grid*, 2016.

[173] R. Diestel, *Graph theory*, 4th. Springer, 2010.

[174] J.-C. Fournier, *Graph theory and applications*. ISTE Ltd and John Wiley, 2009.

[175] R. Caire (ed.), *Self healing philosophy and operation process (automatic reconfiguration based on fault location outputs)*, Deliverable D7.3 of the INTEGRAL project, 2011.

[176] K. Paton, “An algorithm for finding a fundamental set of cycles of a graph”, *Communications of the ACM*, vol. 12, no. 9, pp. 514–518, 1969.

[177] B. de Metz-Noblat, F. Dumas, and C. Poulain, “Cahier technique no. 158: Calcul des courants de court-circuit”, Schneider Electric, Tech. Rep., 2005.

[178] P. L. Cavalcante, J. C. López, J. F. Franco, M. J. Rider, A. V. Garcia, M. R. R. Malveira, L. L. Martins, and L. C. M. Direito, “Centralized self-healing scheme for electrical distribution systems”, *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 145–155, Jan. 2016.

[179] M. Robinson, “The SCADA threat landscape”, in *1st Int. Symposium on ICS & SCADA Cyber Security Research*, 2013, pp. 30–41.

[180] U. Premaratne, J. Samarabandu, T. Sidhu, R. Beresh, and J.-C. Tan, “An intrusion detection system for IEC61850 automated substations”, *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2376–2383, Oct. 2010.

[181] A. A. Cárdenas, R. Berthier, R. B. Bobba, J. H. Huh, J. G. Jetcheva, D. Grochocki, and W. H. Sanders, “A framework for evaluating intrusion detection architectures in advanced metering infrastructures”, *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 906–915, Mar. 2014.

[182] *Das Smart Meter Gateway*, Bundesamt für Sicherheit in der Informationstechnik, 2014.

[183] S. S. Wu, C. C. Liu, and A. Stefanov, “Distributed specification-based firewalls for power grid substations”, in *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Oct. 2014.

[184] T. Hecht, L. Langer, and P. Smith, “Cybersecurity risk assessment in smart grids”, *Tagungsband ComForEn 2014*, 2014.

[185] W. Wang and Z. Lu, “Cyber security in the smart grid: Survey and challenges”, *Computer Networks*, vol. 57, no. 5, pp. 1344–1371, 2013.

[186] T. U. Vélez and M. M. Morana, *Risk centric threat modeling*. Wiley, 2015.

[187] X. Li, X. Liang, R. Lu, X. Shen, X. Lin, and H. Zhu, “Securing smart grid: Cyber attacks, countermeasures, and challenges”, *IEEE Commun. Mag.*, vol. 50, no. 8, pp. 38–45, Aug. 2012.

[188] *A reference security management plan for energy infrastructure*, Prepared by the Harnser Group for the European Commission, 2010.

[189] E. Handschin, F. Schweppe, J. Kohlas, and A. Fiechter, "Bad data analysis for power system state estimation", *IEEE Trans. Power Apparatus and Systems*, vol. 94, no. 2, pp. 329–337, Mar. 1975.

[190] A. Monticelli and A. Garcia, "Reliable bad data processing for real-time state estimation", *IEEE Trans. Power Apparatus and Systems*, vol. PAS-102, no. 5, pp. 1126–1139, May 1983.

[191] O. Kosut, L. Jia, R. Thomas, and L. Tong, "Malicious data attacks on the smart grid", *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 645–658, Dec. 2011.

[192] Y. Liu, P. Ning, and M. K. Reiter, "False data injection attacks against state estimation in electric power grids", *ACM Transactions on Information and System Security (TISSEC)*, vol. 14, no. 1, 2011.

[193] M. Costache, V. Tudor, M. Almgren, M. Papatriantafilou, and C. Saunders, "Remote control of smart meters: Friend or foe?", in *7th European Conf. Computer Network Defense*, Sep. 2011, pp. 49–56.

[194] W. Temple, B. Chen, and N. Tippenhauer, "Delay makes a difference: Smart grid resilience under remote meter disconnect attack", in *IEEE Int. Conf. on Smart Grid Communications (SmartGridComm)*, Oct. 2013, pp. 462–467.

[195] *Continental Europe operation handbook*, [Accessed: 18/07/2017], ENTSO-E. [Online]. Available: `www.entsoe.eu/publications/system-operations-reports/operation-handbook/Pages/default.aspx`.

[196] *Hinweise zum Bedarf*, [Accessed: 18/07/2017], Internetplattform zur Vergabe von Regelleistung. [Online]. Available: `www.regelleistung.net/ext/tender/remark`.

[197] E. Handschin, *Elektrische Energieübertragungssysteme*. Dr. Alfred Hüthing Verlag Heidelberg, 1987.

[198] D. Fetzer, G. Lammert, and M. Braun, "A flexible matlab/simulink RMS-framework for electrical power systems designed for research and education", in *To be published at PSCC 2018*, 2018.

[199] R. Lasseter, "MicroGrids", in *IEEE Power Engineering Society Winter Meeting*, vol. 1, 2002, pp. 305–308.

[200] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management", *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 54–65, May 2008.

[201] J. Guerrero, M. Chandorkar, T. Lee, and P. Loh, "Advanced control architectures for intelligent microgrids - Part I: Decentralized and hierarchical control", *IEEE Trans. Industrial Electronics*, no. 4, pp. 1254–1262,

[202] J. Peas Lopes, C. Moreira, and A. Madureira, "Defining control strategies for MicroGrids islanded operation", *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 916–924, May 2006.

[203] A. Khodaei, "Resiliency-oriented microgrid optimal scheduling", *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1584–1591, Jul. 2014.

[204] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini, "Enhancing power system resilience through hierarchical outage management in multi-microgrids", *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2869–2879, Nov. 2016.

[205] G. Klein, J. Andronick, K. Elphinstone, G. Heiser, D. Cock, D. E. Philip Derrin and, K. Engelhardt, R. Kolanski, M. Norrish, T. Sewell, H. Tuch, and S. Winwood, "seL4: Formal verification of an operating-system kernel", *Communications of the ACM*, pp. 107–115, Jun. 2010.

[206] M. Slezak, *Unhackable kernel could keep all computers safe from cyberattack*, [Accessed: 18/07/2017], New Scientist. [Online]. Available: `www.newscientist.com/article/mg22730392-600-unhackable-kernel-could-keep-all-computers-safe-from-cyberattack-2/`.

[207] European Comission, *Technology readiness levels (TRL)*, Horizon 2020 - Work Programme 2014 - 2015, 2014.

[208] M. Vogt, F. Marten, L. Lower, D. Horst, K. Brauns, D. Fetzer, J. H. Menke, M. Troncia, J. Hegemann, C. Tobermann, and M. Braun, "Evaluation of interactions between multiple grid operators based on sparse grid knowledge in context of a smart grid co-simulation environment", in *IEEE PowerTech Eindhoven*, Jun. 2015.

[209] *OpSim - Test- und Simulationsumgebung für Betriebsführung und Aggregatoren*, [Accessed: 01/09/2017], Fraunhofer IWES. [Online]. Available: `www.energiesystemtechnik.iwes.fraunhofer.de/de/schnelleinstieg-wirtschaft/themen/opsim.html`.

[210] *Données du distributeur*, [Accessed: 18/05/2017], Strasbourg Électricité Réseaux. [Online]. Available: `www.strasbourg-electricite-reseaux.fr/nous-connaitre/donnees-du-distributeur`.

[211] Conseil international des grands réseaux électriques. Comité d'études C6, *Benchmark systems for network integration of renewable and distributed energy resources*. CIGRÉ, 2014.

[212] *The JavaScript Object Notation (JSON) Data Interchange Format*, RFC 7159, Mar. 2014.

[213] *Jackson JSON Tutorials*, [Accessed: 18/05/2017], FasterXML. [Online]. Available: `github.com/FasterXML/jackson-docs`.

[214] *Extensible Messaging and Presence Protocol (XMPP): Core*, RFC 6120, Mar. 2011.

[215] *Internet of Things (IoT)*, [Accessed: 20/06/2017], XMPP Standards Foundation. [Online]. Available: `xmpp.org/uses/internet-of-things.html`.

[216] *Communication networks and systems for power utility automation - Part 8-2: Specific communication service mapping (SCSM) - Mapping to Extensible Messaging Presence Protocol (XMPP)*, IEC 61850-8-2, 2015.

[217] *Smack 4.2.0*, [Accessed: 20/06/2017], Ignite Realtime. [Online]. Available: `www.igniterealtime.org/projects/smack/index.jsp`.

[218] *Openfire 4.1.4*, [Accessed: 20/06/2017], Ignite Realtime. [Online]. Available: `igniterealtime.org/projects/openfire/`.

[219] F. Christian, "Probabilistic clock synchronization", *Distributed Computing*, 1989.

[220] *JFreeChart*, [Accessed: 21/06/2017]. [Online]. Available: `www.jfree.org/jfreechart/`.

[221] P. Boursier, C. Mullon, F. Pelletier, M. Souris, and J.-P. Treuil, "PRAO : Un système d'information géographique : Outil de "Planification Régionale Assistée par Ordinateur"", FRE, *TSI : Technique et Science Informatiques*, vol. 4, pp. 523–538, 1985.

[222] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to algorithms*. The MIT Press, 2009.

[223] B. T. Richardson, *JPowerFlow*, [Accessed: 21/06/2017], Sandia National Laboratories. [Online]. Available: `jpowerflow.sourceforge.net/index.html`.

[224] R. D. Zimmerman, "Comprehensive distribution power flow: Medeling, formulation, solution algorithms and analysis", PhD thesis, Cornell University, 1995.

[225] J.-H. Teng, "A direct approach for distribution system load flow solutions", *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 882–887, Jul. 2003.

[226] F. C. Schweppe and J. Wildes, "Power system static state estimation, Part I: Exact model", *IEEE Trans. Power Apparatus and Syst.*, vol. PAS-89, no. 1, pp. 120–125, Jan. 1970.

[227] *Class ChiSquaredDistribution*, [Accessed: 10/07/2017], Apache. [Online]. Available: `commons.apache.org/proper/commons-math/javadocs/api-3.3/org/apache/commons/math3/distribution/ChiSquaredDistribution.html`.

[228] M. Kraiczy, T. Stetz, and M. Braun, "Parallel operation of transformers with on-load tap changer and photovoltaic systems with reactive power control", *IEEE Trans. Smart Grid*, 2017.

[229] G. Marsaglia, "Xorshift RNGs", *Journal of Statistical Software*, Jul. 2003.

[230] *JGraphT 0.9.1*, [Accessed: 13/07/2017]. [Online]. Available: `jgrapht.org/`.

[231] "Oracle VM VirtualBox", Oracle Corporation, User Manual Version 5.1.18, 2017. [Online]. Available: `www.virtualbox.org`.

[232] *JavaFX - The rich client platform*, [Accessed: 14/08/2017]. [Online]. Available: `www.oracle.com/technetwork/java/javase/overview/javafx-overview-2158620.html`.

[233] *Easergy T300 - A powerful remote terminal unit (RTU) for feeder automation*, [Accessed: 18/05/2017], Schneider Electric. [Online]. Available: `www.schneider-electric.com/en/product-range-presentation/62399-easergy-t300`.

[234] "Sharing information between coreDB and a Java API", Schneider Electric - Telvent, Description, 2015.

[235] *The importance of open protocols*, [Accessed: 18/05/2017], Open Charge Alliance. [Online]. Available: `openchargealliance.org/protocols/`.

# Acknowledgements

*En mémoire de Patrick*

The work of this thesis has been partly funded by the European Commission under FP7 grant agreement 609359 “DREAM”.

The author of this thesis is grateful for the scholarship provided by the Graduiertenakademie of the University of Kassel.

ISBN 978-3-7376-0592-2

This thesis is about the design and the implementation of a resilient grid operation for the distribution grid. This research question is induced by the advancing of three trends: Decarbonisation, decentralisation and digitalisation. These three trends transform the hitherto passive distribution grid into an active system that contains an active operation. The term "resilience" describes capabilities of the system to absorb, to adapt, and to recover from faults and disturbances. This concept is realised on the one hand with the choice of the operation architecture, on the other hand for the choice of possible methods and functions.

This thesis develops a distributed-hierarchical operation architecture. For this architecture several methods have been developed that optimally benefit from the operation architecture and that allow the fully automated operation of the distribution grid. For that purpose a heuristic optimisation has been developed to solve problems like voltage profile violations and congestions. Another important method, especially with regard to resilience, is the self-healing capability to resupply clients after permanent faults.

kassel
university
press