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Technological University Dublin

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Thesis - Main Volume

A thesis submitted for the degree of Doctor of Philosophy to the Technological University Dublin

Supervised by
Prof. Dr. Michael Conlon and Prof. Dr.-Ing. Dieter Metz

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Dublin 8

October 2018

Darlus France Mengapche
DEDICATED TO
MY SONS
AND
MY WIFE
Abstract

The major changes in distribution networks (medium and low voltage networks) over recent decades led to new challenges and issues in the operational management of these networks. Amongst others, issues such as load flow problems (power flow reversal, overloading of network equipment, network congestions), voltage problems (voltage limit violations, voltage increases and decreases, harmonics), power schedule management problems, network state estimation and problems with the operation of protection equipment could be encountered. Besides, the control center staff which is confronted with new complex tasks, challenges and responsibilities, must be prepared and trained for the operational management of the future distribution grid, so-called “Smart Grid”. In this thesis, the presentation of the possible structure and operation of Smart Grids, the development of some very important tools for the operational management of Smart Grids, and, the development of a dynamic power training system to prepare and train control center staff for the operational management of Smart Grids are target and performed. The methodology of “quadriculation” is used in this thesis. It encompasses survey, simulation, action research and case study. The presented possible structure and operation of Smart Grids enable many advantages in the network operational management and also enable a support of the control center staff. Applying the described and developed tools for the operational management of Smart Grids, the mentioned issues occurring in nowadays distribution grids could successfully, effectively and efficiently be solved. A first training experience of the control center staff with the network training system was successfully undertaken at the control center of the DSO RMN in Darmstadt, Germany. The training was evaluated by the DSO and the control center staff to be interesting, important, useful and innovative. The control center staff could clearly understand the challenges and problems in distribution grids. Various scenarios could be trained, different strategies and solutions to problems could be experimented, and advantages and disadvantages could be deduced and discussed. The DSO control center staff described the increase of knowledge and skills as significant. The results of the Smart Grid description and of the tools for the operational management of Smart Grids can be used as input for further development and practical application of software tools, hardware equipment and real Smart Grids.
Declaration

I certify that this thesis which I now submit for the confirmation examination for the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Technological University Dublin and has not been submitted in whole or in part for another award in any other third level institution.

The work reported on in this thesis conforms to the principles and requirements of the TUD's guidelines for ethics in research.

TUD has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Signature ___________________________ Date ______________

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Finally, I would like to thank all everyone who contributed directly or indirectly to the successful realization of this thesis.

Darlus France Mengapche
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<th>Description</th>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>BDEW</td>
<td>Bundesverband der Energie- und Wasserwirtschaft e.V</td>
</tr>
<tr>
<td>BMUB</td>
<td>Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DSO</td>
<td>Distribution System Operator</td>
</tr>
<tr>
<td>EEG</td>
<td>Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)</td>
</tr>
<tr>
<td>EN</td>
<td>European Normative</td>
</tr>
<tr>
<td>EnWG</td>
<td>Energiewirtschaftsgesetz (Energy Act)</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FACTS</td>
<td>Flexible Alternating Current Transmission Systems</td>
</tr>
<tr>
<td>FNN</td>
<td>Forum Netztechnik/Netzbetrieb</td>
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<tr>
<td>GA</td>
<td>Grid Area</td>
</tr>
<tr>
<td>GM</td>
<td>Grid Manager</td>
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<tr>
<td>HRC fuses</td>
<td>High Rupture Capacity fuse</td>
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<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commision</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage</td>
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<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>MATLAB</td>
<td>MATrix LABoratory (software)</td>
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<td>MG</td>
<td>Mini Grid</td>
</tr>
<tr>
<td>MGM</td>
<td>Mini Grid Manager</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<tr>
<td>P-f control</td>
<td>Active power – frequency control</td>
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<tr>
<td>pu</td>
<td>Per-Unit</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>Q-V</td>
<td>Reactive power - Voltage</td>
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<tr>
<td>RTU</td>
<td>Remote Terminal Unit</td>
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<tr>
<td>SCADA</td>
<td>Supervisory And Data Acquisition</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>SG</td>
<td>Smart Grid</td>
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<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>VDE</td>
<td>Verband der Elektrotechnik</td>
</tr>
<tr>
<td>VDI</td>
<td>Verein Deutscher Ingenieure</td>
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<tr>
<td>VDN</td>
<td>Verband der Netzbetreiber</td>
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<tr>
<td>V-PQ</td>
<td>Voltage - Active power - Reactive power</td>
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<td>V-Q control</td>
<td>Voltage - Reactive power control</td>
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<td>µG</td>
<td>Micro Grid</td>
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Chapter 1  Introduction

1.1  Background and problem statement

Within its climate and energy policy, the European Union (EU) enacted in 2009 a package of directives and targets under the name “20-20-20 targets”. Accordingly, the following goals should be achieved by the year 2020 across Europe [1]:

- A reduction of greenhouse gas emissions by 20% (compared to the emission level in 1990).
- An increase of the shares of renewable energies in the total energy consumption by 20%.
- An increase in energy efficiency by 20%.

Besides, key targets for the years 2030 [2] and 2050 [3] have been defined.

For the achievement of the goals, all EU member states are obliged to provide their contributions with respect to differentiated national targets, which are determined in a “burden sharing” process [4].

In the Federal Republic of Germany, the defined national targets are realized within the big national project entitled “Energiewende” (in Engl. “Energy revolution”). Here, the integration of renewable energy generation plants in existing grids is intensified by means of investment incentives in order to replace fossil-fuelled power plants (e.g. coal power plants, oil power plants) and also nuclear power plants. Large offshore/onshore wind farms and photovoltaic parks of great power scale are connected to the extra high and high voltage network levels, renewable energy generation plants of medium power scale (e.g. biogas power plants, wind turbines, photovoltaic plants) are integrated in medium voltage network level and renewable energy generation units of small power scale (e.g. photovoltaic systems on roofs) are connected to the low voltage network level. A major boost for the acceleration of this project was brought about by the devastating nuclear disaster in Fukushima (Japan) in 2011. As a consequence of this event, 8 nuclear power plants were immediately shut down. The shutdown of the remaining 9 is planned to be undertaken before 2022.
For increasing the energy efficiency, measures such as the incorporation and use of better insulation materials in residential buildings and the promotion of energy efficient appliances among other measures are planned.

In particular distribution networks (medium and low voltage networks) were initially planned, built and used almost exclusively for the distribution of electrical energy to consumers. These networks were therefore considered as “passive networks”. But since recent decades, an increasing and large scale integration of decentralized generation units in these networks is occurring. This integration leads to a transformation of distribution networks from “passive networks” to “active networks”. However, this transformation causes the occurrence of new problems in these networks. Due to the characteristic intermittent power infeed of renewable energy generation plants (mainly wind turbines and photovoltaic systems), the total production can already exceed the total consumption in some distribution networks on occasion. Load flow problems (power flow reversal, overloading of network equipment, network congestions), voltage problems (voltage limit violations, voltage fluctuations, flickers, harmonics, voltage unbalances), power schedule management problems (compliance with schedules at network delivery points), network state estimation and problems with protection equipment (which do not react properly in some cases) are among some of the new problems encountered more frequently in distribution networks. These problems represent new challenges in future distribution network operation. Therefore, new and efficient approaches and measures for addressing these problems are needed. Thus, equipment damage, grid collapse and, even worse, electrical hazards to humans must be prevented and avoided. Compared to the current operation of distribution networks, the future operation has another dimension and is considerably more complex.

Furthermore, the lack of observability and controllability of these networks represent a further significant issue. So far, distribution networks were operated in a “blind” mode (no monitoring and control possibilities were available). The installation of sensors and ICT (information and communication technology) was hardly necessary as the networks were passive and the load behaviour was rather predictable to a significant extent. Since these networks are becoming active, network monitoring to gain an overview of the network situation and to identify potential problems is imperative. Apart from
monitoring, the network control (sending switching commands, adjusting the states of components in the network) is also important.

These changes in distribution networks lead to new challenges in the network operational management and these challenges will generate new requirements. These requirements and challenges need to be addressed in order to avoid a possible deterioration in the network reliability, supply security and supply quality.

The control center staff is also concerned by these changes which leads to new network operational situations, new tasks and new responsibilities. The control center staff must react through acquisition of necessary skills and knowledge. Therefore, a further professional qualification by an adequate training is urgent and indispensable.

In this thesis, the following main questions need to be answered:
What is the impact of the mentioned new changes and problems on distribution networks? How could future distribution networks be structured and operated? How can the control center staff of DSOs be trained in an efficient manner for the future network operation? How should the training be designed? What software tools could provide support and make operational recommendations in the case of complex operator decisions?

1.2 Goals to be achieved

The following main goals are to be achieved at the end of this thesis:
- Development of a dynamic power training system to prepare and train control center staff for the operational management of Smart Grids.
- Development of tools for the operational management of Smart Grids

The research objectives listed in Section 1.3 represent segments for bridging the gap between the actual particular situation in distribution networks as mentioned in Section 1.1 and the main goals to be achieved. Therefore it is absolutely important and essential to handle each of these research objectives which are reflected in the chapters of this thesis and thus making out this thesis a “project of capstone nature”.

Darlus France Mengapche
1.3 Research objectives

The research objectives are:

- Investigation and description of changes in the electrical power supply. The focus is on transmission and distribution networks.
- Description of future distribution networks, so-called “Smart Grids”.
- Reasons for the necessity of training of control center staff. Identification and comparison of different training methods, then selection of the most appropriate and efficient method for the training of control center staff.
- Concept, design, implementation and testing of a dynamic power training system for training the control center staff.
- Analysis, concept, design, implementation and testing of various software tools for the operational management of future distribution networks (Smart Grids).
- Installation and commissioning of a dynamic power training system at the control center of the DSO RMN (Rhein-Main-Neckar) in Darmstadt.
- Preparation, planning and training of the control center staff of the DSO RMN and evaluation of the training.

1.4 Research method

The methodology of “quadriculation” is used in this thesis. It encompasses survey, simulation, action research and case study.

Initially, a survey of some network operators and experts about the new problems and challenges resulting from the changes in distribution grids was carried out. The nature, frequency, impact and consequences of these problems were investigated to have a clear picture of the issues. Based on the results of this investigation, possible solutions were outlined. Additionally, legislation, regulations, guidelines, recommendations and other documents with respect to the problems and the network operational management were analyzed. The collected information forms the basis for the development of equipment models (including photovoltaic plants, wind turbines, energy storage units and protection devices) and of new functionalities (including feed-in management, frequency-dependent active power output) needed for the training of the control center staff.
In order to create the simulation and dynamic training platform, an existing real-time power grid simulator formerly developed at the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da), has been extended with the developed equipment models, the developed functionalities, new trainer functions, new trainer interfaces and new displays on the workstation. This dynamic power grid simulator is coupled to a standard SCADA system (RESY-PMC©) in order to simulate the environment in control centres and to make the operations on SCADA systems as authentic as possible. Both systems (SCADA and real-time power grid simulator) are linked together to form the so-called "network training system".

In the “action research”, new approaches and useful tools have been developed to effectively mitigate the new problems occurring in distribution networks. These tools support the control center staff and provide improved efficiency in the network operation.

For the practical implementation and demonstration of the obtained results, a “case study” has been conducted. Within this case study, a training concept has been developed together with the local DSO RMN in Darmstadt to prepare and train its control center staff for the future network operation. A training of the control center staff with the DSO’s network model rather than with a generic network model was considered by the DSO as very important. Therefore, the distribution network of the DSO RMN was modelled in the network training system and thus a real-time simulation of the real network was generated.

In addition, a training manual for the staff training was conceived. It describes the operation of the network training system, explains some theoretical basics of electrical power grids and of future distribution networks, so-called “Smart Grids”. The manual also contains several training scenarios designed on the basis of the results from the survey.

After the implementation and installation of the training system in the control center, the training was first conducted with a small number of DSO RMN control engineers. After the first training round, updates were performed on the network training system based
on feedback received (new requirements, changes, extensions, adjustments) from the trained staff. Finally, the entire control center staff (around 15 persons) of DSO RMN performed the training in the year 2015 in Darmstadt.

The case study showed clearly that the new challenges in future distribution network operation can be tackled by this type of real-time simulation and risk-free training.

1.5 Organization of the thesis

The thesis has one abstract, 8 chapters and a supplementary volume.

Chapter 1 is the introduction of the thesis.

Chapter 2 deals with the changes in the electrical power supply system and investigates the new challenges and problems related to these changes. The focus is mainly on transmission and distribution networks.

Chapter 3 presents the future distribution grids, so-called “Smart Grids”, their possible structure and their operation. It deals also with the new responsibilities of Distribution System Operators, the complexity of the tasks to perform in the control center and the training needs of the control center staff.

Chapter 4 deals with the training of the control center staff. It investigates the training necessity of the control center staff and possible training methods. It also presents the importance of a training evaluation and how it can be conducted.

Chapter 5 presents the development of a dynamic power training system for training the control center staff.

Chapter 6 deals with the development of some important tools for the operational management of Smart Grids.
Chapter 7 details the case study conducted with the DSO RMN in Darmstadt and presents the results.

Chapter 8 is the final summary of the thesis.

For sake of clarity, some details have been moved to the supplementary volume accompanying this thesis.

1.6 Main contribution

The investigation and simulation of new challenges in distributed network presented in Section 2.4.3, the implementation of the tools presented in Chapter 6 and the expansion (data model and visualization) of the network presented in Chapter 7 were successfully realized in supervised projects [5, 6, 7, 8, 9] during this thesis. The ideas, the concepts and the design of each project were originally from me. Only the implementations were conducted under my strict supervision and guidance by the respective students.

Besides, the rest of the work (ideas, concepts, design and realization/implementation) in the thesis were completely and successfully done by myself.
Chapter 2  Changes in the Electrical Power Supply

2.1  Introduction

For many years, the worldwide production of electrical energy is mainly based on the combustion of fossil primary energy sources (such as coal, oil, gas). Thereby, greenhouse gases are produced and emitted into the atmosphere. These gases unfortunately damage and transform the climate worldwide. As a result, severe climate events such as floods, storms and droughts having disastrous consequences for humans and the environment are occurring with more frequently.

As a response, the European Union (EU) adopted in 2008 as part of its climate and energy policy, a set of guidelines and targets for the protection of the environment. However, the implementation of these goals leads to major changes in the electrical power supply landscape. All actors in the electrical power supply sector are concerned by these changes and are thus confronted with new challenges, problems, and requirements. In this chapter, the focus is exclusively on the actors “Transmission System Operator” and “Distribution System Operator”.

In Section 2.2, the objectives adopted by the EU and their associated challenges are presented. The frameworks that have been set for the implementation of these objectives are given in Section 2.3. Due to these changes in the electrical energy supply landscape, new challenges and problems arise in transmission and distribution networks. These are described in Section 2.4.

2.2  Objectives and challenges

The European Union (EU) decided in 2008, as part of its climate and energy policy, a set of guidelines and targets under the name “20-20-20 targets”. According to the policy, by the year 2020:

- a reduction of greenhouse gas emissions by 20% (compared to the emission level in 1990),
- an increase of the proportion of renewable energies in the total energy consumption by 20% and
- an increase of energy efficiency by 20%
should be achieved throughout Europe [1].

2.2.1 Reduce greenhouse gas emissions

The reduction of greenhouse gas emissions is to be achieved through a reduction of the proportion of fossil-fuelled power plants in the total power generation portfolio. This reduction should not occur abruptly, but continuously over a given time period. **Figure 2.1** shows the development of the electrical energy production from different energy sources from the year 2005 to the year 2050 (forecast) in Germany.

![Figure 2.1 Development of the electrical energy generation from different energy sources in Germany](image)

These fossil-fuelled power plants will be substituted by climate-friendly power plants. In the year 2014 the plan was largely on schedule apart from a deficit in biomass production and a higher level of production from coal plants.

Since the climate problem is global, all nations should contribute to the solution. However, the allocation of contributions is controversial and to some extent contentious. Currently, many nations have failed to comply with the Kyoto protocol and with the decisions from following World Climate Forums. On the 13.04.2014, the
IPCC (Intergovernmental Panel on Climate Change) released an alarming report on the climate problem. It is stated in the report that many developed countries are still emitting excessive greenhouse gases and the emissions of developing countries is continuously rising [9, 10, 11]. The United Nations Climate Change Conference held in 2015 in Paris is the most recent attempt to deal with the mitigation of greenhouse gas emissions. It ended with the adoption of the Paris Agreement. This agreement’s central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change [12]. Reliable agreements between nations, closer collaboration and cooperation, technological and financial development supports are clearly needed to achieve the reduction of greenhouse gas emissions.

2.2.2 Increasing the proportion of renewable energies

The increase of the proportion of renewable energies in the total energy consumption targets together with the reduction of greenhouse gas emissions from the energy production requires the substitution of fossil-fuelled power plants. It can be seen in Figure 2.1 that the proportion of renewable energies in total energy production is increasing since 2005 and will keep on increasing in the future based on current forecasts. Over the same time interval, the proportion of fossil energy in the total energy production is decreasing and will continue to decrease in the future.

However, the substitution of fossil-fuel power plants by renewable energy plants presents significant challenges. The generation of electrical energy is tightly bound to energy consumption. In order to maintain constant network frequency and given the fact that the power grid itself cannot store energy, the total power production must always meet the total power demand at every time instant. To achieve this, the power output of fossil-fuelled power plants can be well controlled and can be maintained constant in some situations. In contrast, the power outputs of wind turbines and photovoltaic systems are intermittent. The power generated by wind turbines depends on the cube of the wind speed (the rotating mass of the system has a partial damping effect). In the
case of photovoltaic systems, the output power is nearly linearly proportional to the solar irradiation. Therefore, changes in the wind speed and solar irradiance cause fluctuations in the power output.

The power output of fossil-fuelled power plants is well and accurately schedulable to meet the energy demand. In the case of wind turbines and photovoltaic systems, good forecasts (weather forecasts, energy production forecasts) are absolutely indispensable to schedule the power output with respect to the demand. Nevertheless, it is not guaranteed that the scheduled power will really be generated because the weather conditions (wind speed, wind direction, temperature, solar irradiance, cloud) during the operation can be different from the forecasted weather conditions. Therefore, energy storages systems are needed to compensate deviations in the schedule (energy surpluses, energy deficits). The following use cases are possible:

- Combination wind turbine and energy storage system.
- Combination photovoltaic system and energy storage system.
- Installation of energy storage systems in the network.

Approximately 1 km² is necessary to build a coal power plant of 1 GW rated power. A photovoltaic system of the same rated power would need about 20 times more space. A coal power plant can be operated at approximately 8300 annual full load hours. In Germany, photovoltaic plants typically have an annual full load hour of around 1000 h/a and onshore wind turbines have approximately 2000 h/a [13]. It can be derived from these numbers that to the installed power of photovoltaic systems should be 8 times higher and of wind turbines should be 4 times higher in order to achieve the annual full load operational hours of a coal power plant. Particularly in developed countries, the construction of such large plants is not always easy due to resistance from citizens' initiatives, official approvals, natural reserves and geographical conditions. A combination of a relatively small number of large plants and many decentralized small plants (on buildings or roofs) could be a solution.

**Figure 2.2** shows the generated power of wind turbines in 2013 in Germany. Firstly, the fluctuations in the generated power are very noticeable. Secondly, it can be seen that the generated power was always less than the installed power. To achieve the generation of
an average power equal to the installed power shown in the figure, the installed power should be at least 8 times higher than the illustrated installed power.

![Graph showing fluctuating generation of wind turbines in 2013](image)

**Figure 2.2** Fluctuating generation of wind turbines in 2013 [14] (translations in Appendix 13)

### 2.2.3 Increase of the energy efficiency

The increase of energy efficiency has the objective of achieving a more sustainable and more effective use of energy in various sectors (e.g. electricity generation, transport, industry, agriculture, commercial and residential). Among other initiatives, energy-intensive equipment will be replaced by energy-efficient alternatives, buildings will use energy more efficiently (e.g. improved heating and lighting) and greater efficiency in transport will be introduced.

**Figure 2.3** shows the prediction of primary energy consumption from the German Ministry of Environmental Protection.
Figure 2.3 Development of the primary energy consumption during the next decades in Germany (past and future) [8]

2.3 Frameworks

2.3.1 Technical frameworks

To achieve the changes in the energy supply and to continue to ensure a secure, safe and reliable network operation, guidelines and standards were developed at European and national levels. These summarize important rules and aspects which form the economic and procedural basis of grid usage and serve the technical and operational coordination between the network operators and network users. These serve also as planning documents and decision support. At the European level, the ENTSO-E Operation Handbook [15] and standards such as EN 50160 [16] amongst others have been put into operation. These can then be directly implemented at national level, or be changed and adjusted to specific local conditions. In Germany, the Transmission Code [6], the technical connection requirements [17], the guidelines for connection and parallel operation of generation facilities in extra-high voltage and high voltage networks [18] amongst others were implemented for TSOs. The implementation of the Distribution Code [19], the technical connection requirements [20, 21], the guideline for connection and parallel operation of generation facilities in the medium voltage network [22], the
guideline for connection and parallel operation of generating capacity in the low voltage network [23] was performed for DSOs.

2.3.2 Economic frameworks

As new and in some cases not yet mature technologies (energy storage systems, renewable energy plants like wind turbines, photovoltaic systems) with rather high marginal costs are used in the development of a sustainable, secure, affordable, efficient and environmentally friendly energy supply, some laws have been enacted to specify economic frameworks. These frameworks should enable a priority grid connection and a priority infeed of these technologies. These frameworks also create incentives (including promotion, allowances and subsidies) to increase the uptake and the use of these technologies. Additionally, these frameworks also promote further research and development for the improvement of these technologies.

In Germany, the Energy Act (in German: EnWG – Energiewirtschaftsgesetz [24]) and the Renewable Energy Act (in German: EEG - Erneuerbare-Energien-Gesetz [25]) are applied.

2.3.3 Regulatory frameworks

Before liberalization of electricity supply, utility companies were responsible for the generation, transmission, distribution and sale of energy. These companies had a so-called “vertically integrated structure”. Thus, they had a natural monopoly over the entire energy supply value chain and had a big influence on several aspects (e.g. political implementation, social policy and pricing policy).

The transmission and distribution grid departments of the utility companies were responsible for the transmission and distribution of electrical energy, supply security, supply reliability and supply quality. They were responsible for the network operation, servicing, expansion, extension, maintenance and repair among a range of tasks. As it is not economically justified to build and operate multiple parallel power grids, network operators were obliged to grant non-discriminatory network access to independent
energy producers and, to transmit and distribute the generated energy from these producers. Network operators were paid for those services. To temper the effects of the monopoly market and to monitor the compliance of their activities with regulations and to regulate their activities, network operators were placed under the supervision and regulation of a regulatory agency (in German: Bundesnetzagentur).

In general, generation and energy retail companies were not regulated those days.

![Diagram of utility company with divisions for generation, transmission, distribution, and retail]

**Figure 2.4 Energy sector before liberalization**

The structure of the energy supply before liberalization had some advantages and disadvantages. The fact that the 4 operating companies (generation, transmission, distribution and sales companies) were under one roof had some advantages such as:

- The easy and quick exchange of information between each company in the utility.
- A better and easy coordination, execution and optimization of both technical and economic processes with each other.
- A simplified and optimal decision-making, as information and data from individual companies were involved.
- Better planning and, ability to commission and construct the necessary expensive bulk generation power plants.

Some disadvantages of this structure were, among others:

- The monopoly nature of utility companies meant that they held considerable power, dominance and influence in the energy sector.
- No transparency of network operations regarding possible discrimination of market participants (e.g. other generation and sales companies not belonging to the utilities).
- Possible cross-subsidization of the non-regulated companies of utility companies by their regulated companies.
The strong dependency of consumers due to the monopoly nature of the utilities, as most consumers did not have any supplier choice.

The liberalization of the energy sector led to an unbundling (separation) of the 4 main business areas of the vertically integrated utility companies into independent companies. This unbundling resulted in the creation of legally, organizationally, accounting and socially independent companies (generation, transmission, distribution and sales companies).

Some aims of the liberalization were to open the market to more participants, to create more competition, to reduce the energy price and thus to offer this energy at a low price as possible to the consumers. Through the liberalization, consumers could also have the possibility and flexibility to easily choose their energy suppliers. Even with liberalization, transmission and distribution companies remained under regulation.

2.4 Electrical power grids

In recent years, the energy supply in Germany was based on a central top-down structure. The energy was produced mostly by a relatively small number of large power plants, which were almost all connected to the transmission network. The energy produced was delivered via the transmission network to large loads, and via the distribution network to medium and small loads. The energy flow was unidirectional and directed from the transmission network to the distribution network. Since on the one side, most loads throughout the network are not completely predictable and behave
stochastically, and on the other side, existing power plants (fossil-fuelled power plants, pumped storage power plants, gas power plants) are well controlled, the generation was adapted to the consumption. This can be termed consumption-oriented energy generation. **Figure 2.6** shows this structure.

**Figure 2.6** Power flow in the centrally structured energy supply

Due to the substitution of fossil-fuelled power plants by climate-friendly generation plants and due to the massive integration of renewable energy plants in all network levels, the power supply changes from the previously centralized structure towards a decentralized structure (**Figure 2.7**). Here, a relatively small number of large climate-friendly generation plants feed into the transmission system and a large number of small
plants distributed over a wide area feed into the distribution network. This leads very often to a power flow reversal, namely from the distribution network to the transmission network. The energy flow becomes bidirectional. Since the energy supply of most climate-friendly generation plants is intermittent, a consumption-oriented energy generation is no longer enough for a safe and reliable energy supply. To keep the power system stable, it is necessary that the consumption adapts also to the production and this can be termed production-oriented energy consumption. Figure 2.7 shows this new structure.

The changes in the transmission (Subsection 2.4.2) and distribution (Subsection 2.4.3) networks are discussed in the following subsections. The power quality in power grids is discussed in Subsection 2.4.1.
2.4.1 Power quality

Power quality is affected by the changes in the power supply. Power quality in electrical networks is defined as the conformity between the current physical values of the network voltage parameters measured at the consumer interface, and the network voltage characteristics guaranteed by the utility company. A high correlation of the current values with the guaranteed values means high quality [26]. The most important parameters for the identification of the power quality include the voltage value, the frequency, the waveform and the disturbances. Interference emission limits and compatibility levels are determined based on these parameters and utility companies are obliged to comply with these. Often there are utility internal quality objectives, which include much tighter limits.

The disturbances include among others [27]:

- **Harmonics and interharmonics:** They arise in the operation of equipment with nonlinear characteristics and distort the sinusoidal voltage waveform. These include network equipment such as transformers, loads with power electronic components, loads with stochastic behaviour and ripple control devices. The power grid connection of most renewable energy plants is achieved via power electronic devices (such as inverters and converters) and these devices are increasingly integrated into power grids. As a result of this increased integration, a potential increase of the disturbance levels of harmonics and interharmonics in networks is expected.

- **Voltage fluctuations and flicker:** The network voltage is not constant but is continuously subject to fluctuations. A regular or irregular sequence of voltage changes is referred to as voltage fluctuation. These are mainly caused among others by switch-on and switch-off operations of larger loads, load variations, motors and arc furnaces [27]. The growing proportion of renewable energy plants in networks leads to a frequent occurrence of voltage fluctuations in the grid because of their intermittent feed-in behaviour. Voltage fluctuations affect the proper operation of sensitive equipment and facilities. They cause variations in the output of lighting devices, so-called flicker.

- **Voltage unbalances:** In a three-phase system, a voltage unbalance is referred to as whenever the effective values of the phase-to-neutral voltage or the angles between consecutive line voltages (ideally 120°) are not equal. These are due to
the connection of asymmetric loads and single-phase generation plants to the grid, to asymmetric equipment and to the unbalanced operation of symmetric loads. Voltage unbalances occur mainly in distribution networks, especially in low voltage grids. Before the integration of renewable energy plants in distribution networks, mainly loads and network equipment led to voltage unbalances. Nowadays, single-phase renewable energy plants represent an additional cause.

2.4.2 Transmission networks

Figure 2.8, extracted from Figure 2.6 and Figure 2.7, illustrates the transmission networks in a centralized (up) and decentralized (down) structure. In addition to other tasks (such as maintenance, repair, expansion, conversion), TSOs must maintain the power balance in their control areas, keep the voltage within limits, monitor the operating parameters and states as part of the operational management. Due to the changes in the transmission networks described earlier, TSOs will be faced with new challenges in network management. These challenges will induce new requirements. These new challenges and requirements will be discussed in the following subsections.
Figure 2.8 Transmission network in a centralized (up) and decentralized (down) structured energy supply

2.4.2.1 Voltage control

Nowadays, reactive power (inductive and capacitive) is mainly used for voltage control in transmission grids. This reactive power is supplied by reactive power compensation.
units, overhead lines, transformers and generators connected to the grid. In a centrally structured power supply, conventional power plants provided the largest amount of reactive power for voltage control. Due to the decommissioning of these power plants, there is a lack of reactive power in transmission networks. This represents a great danger for the voltage control and the supply security of the power system.

Beside network expansions (this option is lengthy and costly) and tap position settings of transformers (this has an impact on other voltage levels), the following additional options appear as possible solutions for voltage control:

- The installation and operation of additional reactive power compensation units.
- The installation and operation of additional FACTS (Flexible Alternating Current Transmission Systems). These are based on power electronic components configured in series, parallel or combined (series and parallel) and are connected to the grid. Depending on the type, these devices can be used in the network to perform different tasks (including load flow control, voltage control and reactive power control) and to solve various network problems.
- The operation of generators installed in decommissioned power plants as synchronous phase shifters. For this, the generators are converted and operated as idle synchronous motors which provide reactive power. A reference project was carried out on the decommissioned nuclear power plant “Biblis” by the TSO Amprion and the company Siemens. The project was motivated by the identification of potential disturbances in the energy-intensive southern part of Germany due to reactive power shortage after the shutdown of several nuclear power plants in 2011 [28].
- The reactive power supply by renewable energy plants connected directly to the transmission grid.
- The request to connected DSOs to provide reactive power from equipment installed in their respective networks.

2.4.2.2 Power flow management

The shutdown of fossil-fuelled power plants in the south of Germany has led to a lack of generation capacity for load coverage (mainly industrial loads). The high level of
electricity produced in the north through wind turbines (from onshore and offshore wind farms) must be transmitted over existing AC lines to the south. However, in recent years, there have often been temporal congestions on some energy transmission paths. According to investigations and studies carried out by the TSOs and the German Network Agency (DENA), these problems are due to the insufficient capacity on existing transmission lines. It was therefore decided to conduct network upgrades to increase the power transmission capacity in the three-phase system. High-voltage direct current transmission lines (HVDC) are also planned as well as new three-phase lines. **Figure 2.9** shows the planned network expansion measures.

![Network Expansion Diagram](image)

**Figure 2.9** New power lines according to the Energy Development Act [29] (translations in Appendix 13)

To counteract congestions and overloads, TSOs adjust gradually the power output of renewable energy plants by applying “feed-in management” (100%, 60%, 30%, 0% of
the agreed connection active power). This leads naturally to losses because valuable energy is neither fed in nor stored. The costs of non-supplied energy are allocated to all consumers, thus increasing the energy price and so contradicting the low-cost energy supply objective. **Figure 2.10** shows the development of outage energy (incl. outage heat energy) according to § 14 EEG (i.e. German Renewable Energy Act) in GWh.

**Figure 2.10** Development of outage energy (incl. outage heat energy) according to § 14 EEG in GWh (translations in Appendix 13)

### 2.4.2.3 Power compensation

Since the power grid cannot store energy, the entire power production must always match the total required power consumption (load consumption and network losses). The network frequency is a good indicator for this balance. With perfect balance (equilibrium), the frequency is equal to the nominal value (50 Hz in Europe, 60 Hz in the US and Japan). In the event of a sudden mismatch between the total power production and the total power consumption in the network due for example to an outage of a large power plant or a shutdown of a large load, compensation of the power difference is initially achieved through the withdrawal of energy from the rotating masses of power plant turbine sets.
A positive (resp. negative) difference between generation and consumption leads to an increase (resp. decrease) of the network frequency. This frequency deviation should be balanced by means of balancing energy. Plant controls (primary, secondary and tertiary controls) intervene for the provision of the needed balancing energy [5, 30].

**Figure 2.11** gives an overview of the frequency stabilization procedure.

**Figure 2.11** Overview of the frequency stabilization procedure [31]

The primary control monitors the frequency change rate \( \Delta f / \Delta t \) and intervenes to mitigate this frequency change (until \( \Delta f / \Delta t = 0 \)). This primary control power operates according to the principle of solidarity by all power plants having activated frequency control. In the UCTE network, the activation occurs automatically within 30 seconds and the primary control covers a period of \( 0 < t < 15 \) min after the disturbance. After \( \Delta f / \Delta t \) is controlled to \( 0 \), there is a constant frequency deviation from 50 Hz (\( \Delta f_{so} \)) remaining. This is compensated by means of the secondary control.

The secondary control replaces the primary control. In fact, the secondary control intervenes to compensate the frequency deviation from 50 Hz (\( \Delta f_{so} \)). The power for the secondary control is provided by all frequency controlling power plants connected in the control area of the concerned TSO. It is activated immediately and automatically by the concerned TSO. The full power for secondary control must be provided within 5 minutes and the secondary control covers a period of \( 30 \) sec \( t \) \( 15 \) min after the disturbance.
The secondary control is later replaced by the tertiary control. This control is managed by the control center and involves schedule based requests of the concerned TSO to providers of this ancillary service. The power for tertiary control is activated manually and must be fully provided within 15 minutes. This control covers a period of 15 min to 60 min after the disturbance or even several hours in case of several incidents. At latest 60 minutes after the occurrence of the power unbalance, the concerned balancing group manager must have taken care of the balancing.

Considering the substitution of conventional power plants (generators directly coupled to the network) by renewable energy plants (where the power is supplied via power electronic devices), there will be less rotating mass in the power system in the future. This represents a danger for the frequency stability and will cause faster and higher frequency changes in response to sudden power variations. In the period before the intervention of the primary control, frequency protection relays might have eventually already reacted and thus leading to disconnections. An approach to avoid this severe scenario was developed in the Smart Grid Group of the faculty of Electrical Engineering and Information Technology of the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da) and demonstrated in [13]. This work relates to the use of “virtual rotating masses”. These are battery storage systems which are set to behave like the rotating mass of a synchronous generator in the case of frequency changes. Figure 2.12 shows 3 frequency responses to a load disturbance in a simulated interconnected grid. It can be observed that in case of 70% rotating mass from conventional power plants and support from battery storage systems operating as virtual rotating mass, the frequency drop is mitigated more rapidly than in the two other cases. This is due to the fast reaction capability via the power electronics of battery storage systems. After the detection of a frequency change, power is fed via the power electronic interface to stop this frequency change. A combination of central large storage systems and many decentralized small storages systems installed mainly in distribution networks can form a significant large virtual rotating mass.
The delivery of balancing power will represent a big challenge in the future. The substitution of conventional power plants causes a significant reduction of the reserve capacity. Only a small number of power plants will remain in transmission networks. At the same time, the intermittent infeed from renewable energy plants require an increased need for balancing power. The remaining system relevant power plants alone cannot deliver the required balancing power, and therefore cannot always guarantee and maintain the entire system stability. Also these power plants could occasionally be unavailable due to unplanned/planned maintenance, faults or other disturbances.

Renewable energy plants can help to solve this situation. These plants should be included to contribute to system stability. For example in the case where the frequency is high, these plants should reduce their power output at a predetermined gradient in order to counteract the frequency increase. This is already used in practice as required in the standard EN 50549-1/2 and in other regulatory documents [6, 19, 22, 23]. Figure 2.13 shows the procedure applied for wind turbines and PV systems.
2.4.2.4 Restoration of supply

In case of a power outage, the restoration of the power supply must be done as quickly as possible. This is initiated by the relevant TSO with the support of neighbouring TSOs, of connected generators, loads and DSOs. Generators, loads and network segments are switched on successively under the co-ordination of the TSO. This is a difficult undertaking which can take many hours or days (depending on factors such as the outage duration and the power plant states) until the supply is fully re-established.

Because of the lack of large controllable power plants due to the already mentioned substitution of conventional power plants, it will be even more difficult or impossible to carry out a system restoration with only the few remaining controllable power plants in transmission networks. At this point, a new approach is needed. In this concept, the TSO maintains its leading role. However, the DSOs should play a stronger role in the network restoration process and the many small decentralized generation units should take part to this process. The feasibility is explained in more detail in Section 3.3.

Figure 2.13 Active Power Reduction of renewable energy plants in case of overfrequency (actually applied only for wind turbines and PV) [6]
2.4.3 Distribution networks

Figure 2.14, extracted from Figure 2.6 and Figure 2.7, illustrates the distribution networks in a centralized (up) and decentralized (down) structure.

Figure 2.14 Distribution network in a centralized (up) and decentralized (down) structured energy supply

In addition to other tasks such as maintenance, repair, expansion and conversion, DSOs must monitor all operating parameters and states as part of the operational management. Due to the changes in distribution networks mentioned above, DSOs will be faced with new challenges in the network management and these challenges will generate new requirements. These new challenges and requirements will be discussed in the following subsections.
2.4.3.1 Voltage control

The voltage profile from the supplying transformer up to the last node (black line in Figure 2.15) drops due to the operational structure of distribution networks (mainly radial and ring networks) and the presence in the past of predominantly (and exclusively) consumers. Higher and increasing number of producers in distribution networks will lead to a change in the voltage profile. Depending on the infeed of these producers, the node voltages increase at high infeed and the voltage profile appears as illustrated with the yellow line in Figure 2.15.

![Figure 2.15 Voltage profile across a branch in the distribution network](image)

Voltage limit violations can occur at network nodes in the case of high infeed, of certain load/infeed conditions and of certain network topology. The voltage band is set at +/-10% of rated voltage by the standard EN 50160 [16]. Usually DSOs have their own stronger constraints, e.g. +/-3%. The voltages at all nodes in the network should be within this band and in the case of limit violations, measures should be taken to get the
voltage back within this band. **Figure 2.16** gives examples of voltage profiles, including voltage limit violations in the case of high infeed (yellow line), of high consumption (black line) and of a mixed situation of consumption and infeed (red line).

**Figure 2.16** Voltage limit violations in case of high infeed (yellow line) and of high load (black line) in the distribution network

A voltage spread can occur in the case of a high infeed in a network feeder and of a high consumption in a second feeder (**Figure 2.17**). In the worst case, voltage limit violations could appear in both network branches. In this case, adjustments of the transformer tap position are not helpful to solve the problem.
Currently, the tap position of HV/MV transformers is adjusted to deal with voltage problems in distribution networks. This action influences the voltage in the entire distribution network (medium and low voltage networks). However, this may not be sufficient to solve particularly the voltage spread problem mentioned above. As a possible solution, the use of regulating distribution transformers in low voltage networks is in discussion. However, a regulating distribution transformer cannot solve all voltage problems, especially the voltage spread which can arise.

An adjustment of the active and reactive power injections into the grid can positively affect the voltage drops across lines. In this way, voltage problems can be solved. An approach for efficient adjustment of active and reactive power injections for solving voltage problems will be presented in Section 6.4.

Another way to solve voltage problems is through a network expansion. However, this is lengthy, expensive and is not always worthwhile.

Due to the usual configuration of distribution networks and taking as an example the network of the HSE AG company in Darmstadt with about 4000 local substations, it is impossible for the control center staff to simultaneously, optimally and efficiently solve all possible voltage problems encountered in each low voltage network and also to prevent these problems. Here, a local “Grid Manager”, as automatic observer of a feed-in area, is needed for the monitoring of the network and also to solve voltage problems by controlling installed components such as batteries and regulating distribution transformers automatically. In some cases, these Grid Manager need support which would be provided through the intervention of the control center staff. This thesis...
presents one concept of a Grid Manager. A deeper description can be found in Chapter 3.

2.4.3.2 Power flow management

Until the massive integration of generators in distribution networks took place, the power always flowed in one direction from the upstream network over the supplying transformer and the distribution network to the consumers (Figure 2.18). Nowadays, power flow reversals occur more often when the total generation exceeds the total consumption in distribution networks. In this case, power flows back into the upstream network. Thus the power flow becomes bidirectional (Figure 2.19).

![Figure 2.18 Power flow before the massive integration of generators in distribution networks](image1)

![Figure 2.19 Power flow reversal in distribution networks](image2)

Congestion on transformers and lines in networks may occur during a power flow reversal in the case of a high infeed, of certain load situations and of certain network topologies. The occurrence of overloads should be avoided or, if it does occur, they...
must be identified and removed. The current state of technology in distribution networks and in control centres of distribution networks does not enable the identification of overloads (except HV/MV transformers whose loadings are monitored) due to the lack of observability in these networks (no sensors, no measurement devices, no information and communication technology available).

“Masked overloads” are especially dangerous and can occur on lines in distribution networks. This overload type cannot be identified and disconnected by the installed overcurrent protection equipment at the beginning of a feeder. Figure 2.20 shows a power flow reversal and a masked overload in a network. Depending on the network switching state, a high infeed from renewable energy generation plants can lead to a power flow reversal with overload in the middle of the feeder. As some loads on the left side of the overloaded region withdraw power from the network, the detection of the overload by protection devices installed at the feeder is impossible.

In the past as the distribution networks were still passive, the highest current intensity always appeared at the beginning of line tracks. Overloads could be easily identified and disconnected by protection devices installed at the beginning of the feeder (Figure 2.21).

![Figure 2.20 Masked overload in distribution networks](image-url)
As in the case of voltage management (Subsection 2.4.3.1), so-called “Grid Managers”, could monitor the network and solve power flow problems automatically.

2.4.3.3 Protection technology

In the past in distribution networks, protection devices were set in a way that faults could be reliably identified and eliminated given unidirectional power flow. Very often, the settings are left untouched although the power flow in these networks has become bidirectional and these networks are much more dynamic due to intermittent generation units. Therefore, malfunction of protection devices are expected as possible situations are misinterpreted and not identified by protection devices (Figure 2.20).

An economically and technically efficient new network protection concept for active distribution networks is absolutely necessary. The concept should include the existing protection devices as much as possible and, add additional protection devices and sensors at strategic positions in networks.

2.4.3.4 Network monitoring and management

Currently, distribution networks are operated almost blindly. The control center staff receives little or no information about the network state, and it cannot perform any remote actions (e.g. remote switching, influencing of components). Problems and faults in distribution networks are usually not directly registered in the control center, but the control center staff is informed by calls from concerned consumers.

Figure 2.21 Overcurrent protection before the massive integration of generators in distribution networks
Given the new dynamics in distribution grids, monitoring and control capabilities should be provided to ensure reliable, safe and efficient network operation. This is achieved through the installation in these networks of information and communication infrastructures, actuators for remote control, sensors and measurement devices. Given the usual configuration of distribution networks, an installation of measuring devices, actuators and sensors at all nodes and in all lines would cause high unreasonable costs. Therefore at this point, technical possibilities (approaches, software modules) are necessary to achieve the observability and the controllability of distribution networks with the lowest possible number of measurements and at reasonable cost. Such a technical possibility for “state estimation” in networks with a few measurements is one of the subjects of this thesis. It will be presented in Section 6.5.

The amount of information generated by the monitoring of entire distribution networks would depend on the network size and the number of desired parameters to monitor. Depending on the degree of monitoring of entire distribution networks, the transmission of all information to the control center could probably cause some technical problems (e.g. possible overload of control systems and of communication infrastructures, decrease of the data processing throughput, data synchronization problems). In addition, due to a flood of data, the control center staff could not perceive all information and could potentially oversee some important ones. Therefore, strategies for the organization, management and transfer of information are required. These will be discussed and presented in Chapter 3.

2.4.3.5 Control center staff

As shown in the previous subsections, the new challenges in distribution networks will have a very strong influence on the future network operational management. It is foreseeable that the network management will become more complex than in the past. In the network management, new kinds of tasks will appear and some existing tasks will have to be extended in order to continue to provide a stable, efficient, secure and reliable network operation. This represents a new situation for the control center staff.
More than ever in the past, the staff must take over additional responsibilities and will need more skills. Therefore, good preparation of the control center staff through the acquisition of new skills, new working methods and new knowledge is essential.

The control center staff should:

- know the various new challenges and problems, understand their respective origins, understand their impact on the network and learn the possible solutions for efficient (technically and economically) prevention and elimination.
- know the new and extended tasks in the network management. The potentials, added values and execution possibilities of these tasks are to be understood.
- explore the supporting tools (described in Chapter 6) needed to perform its tasks, understand the mode of operation of these tools and learn how to use these. For decision-taking, the staff should be able to interpret the information generated by these tools.

To meet these requirements, basic and advanced trainings of the control center staff are urgently needed. This can be done optimally and risk-free in training sessions. This topic will be discussed deeper in Chapter 4.

2.5 Summary

For the protection and the saving of the climate, the EU wants to achieve the agreed set of guidelines and targets under the name “20-20-20 targets”:

- a reduction of greenhouse gas emissions by 20% (compared to the emission level in 1990),
- an increase of the proportion of renewables in the total energy consumption by 20% and
- an increase of the energy efficiency by 20% by the year 2020 throughout Europe.

For the reduction of greenhouse gas emissions, the proportion of fossil-fuelled power plants to the total power generation should be decreased. At the same time, the substitution of fossil-fuelled power plants with climate-friendly power plants should be undertaken.

Darlus France Mengapche
The increase of the proportion of renewable energies in the total energy consumption should be done through the integration of renewable energy plants in networks. Simultaneously, these units replace the fossil-fuelled power plants. However, the problem with this substitution resides in the generated power by renewable energy generation plants, their availability to meet power demand, their power rating and their generated total energy. The energy production by means of fossil-fuelled power plants can be well planned and dispatched, contrary to the energy production with renewable energy plants which is intermittent.

The replacement of energy-intensive devices by energy-economical alternatives, the more efficient use of energy in buildings, electromobility are some of the changes that will ensure an increase in energy efficiency.

For the achievement of the goals, technical, economic and regulatory frameworks have been established at European and national levels. However, the implementation of these goals leads to large changes in the electrical power supply landscape which concern all actors in the electrical power supply sector. These actors are faced with new challenges, problems and requirements. In this chapter, the focus was set on the actors TSO and DSO. The power quality represents a challenge for both. In addition, the TSO has other challenges in terms of the voltage control, frequency stability, power flow management, power compensation and restoration of supply. The DSO is confronted with challenges in terms of the voltage control, power flow management, protection technology, network monitoring, network management and control center staff training.
Chapter 3  Smart Grids as Future Distribution Grids

3.1  Introduction

In Chapter 2, the changes in electrical networks and, the associated problems and challenges in transmission and distribution networks have been presented. These problems represent threats to the secure, reliable and efficient operation of networks. Unlike transmission networks, distribution networks are not fully automated. That means that the complete network state of a distribution network is unknown for most of the time and control actions cannot be performed. As a consequence, the mentioned problems in distribution networks cannot be identified and the capabilities to perform actions are not available. Thus, the risks in distribution networks are many times higher than in transmission networks. To avert these risks, automation of distribution networks must be undertaken. This automation results in the integration of ICT and intelligence in distribution networks. Thus, the networks become so-called “Smart Grids”.

In Section 3.2, the phrase “Smart Grid” is defined and the group of components in Smart Grids are presented. In addition, the structure and the possible operation of such networks will be explained.

The possible new ancillary services for DSOs (as operators of Smart Grids) are presented and described in Section 3.3. The security and the ICT are of great relevance in Smart Grids. These topics are addressed in Section 3.4. In Section 3.5, it is shown that training of the control center staff is mandatory due to the increasing complexity in network operational management.

3.2  Definition, components, structure and operation

Currently, there is still no set and unified definition for the term “Smart Grid”. Many different definitions of this term can be found in the literature and in different sources. After several years of research and studies on the topic “Smart Grids” in cooperation between:

- the Smart Grid Group of the faculty of Electrical Engineering and Information Technology of the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da),

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• the utility company HSE AG (HEAG Südheissische Energy) and
• the Distribution System Operator RMN (DSO Rhein Main Neckar),

an objective definition of the term “Smart Grid” was established and agreed. This definition is close to the definitions of the NIST [32] and the European Commission [33].

At the same time, an objective vision of the structure, the possible operation and the components have been determined and the results are presented in the following subsections.

3.2.1 Definition and components

According to NIST, a Smart Grid is “a modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications.” [32]

The European Union Commission defines a Smart Grid as “an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety. To do so, Smart Grids coordinate the role of stakeholders involve in the electricity supply chain including generators, grid operators and end users taking into account their needs and capabilities.” [33]

In this thesis, a Smart Grid is defined as:

“A distribution grid cell connected to a transmission system. This distribution grid cell represents the conventional distribution system of a municipal utility or a regional energy utility, and includes a variety of generations (mainly renewable energy generation plants), consumers and energy storages. In addition, the grid cell includes "intelligence" and ICT. ICT is essential for the information and communication networking of the individual components in the distribution grid cell. The intelligence is constituted of algorithms (including for measurement, control, regulation, decision making) and is essential for the efficient, optimal, safe, reliable and sustainable management of the distribution grid cell.”

Figure 3.1 shows a set of components which could be found in a Smart Grid.
Although Smart Grids could have the means to enable network operation, to ensure local supply security, reliability and efficiency, and to solve problems autonomously and locally, these networks should not be operated as self-sufficient and as a stand-alone grid. Smart Grids should cooperate with each other (e.g. energy exchange), should coordinate their actions and should support each other (e.g. in case of problems). The cooperation should be performed for the purpose of grid and system stability. Therefore, Smart Grids should be either directly connected to one another or indirectly via a transmission grid. As an example, consider 2 Smart Grids which are both connected to a transmission grid. A power deficit in one Smart Grid (e.g. due to forecasting errors) could be compensated by the other Smart Grid (having surplus supply capacity) to avoid power balance disturbances in the whole system.
Nevertheless, as long as the technical possibilities and conditions are met, autonomous operation of Smart Grids (e.g. in case of a system-wide problem) should not be excluded.

Collaboration between the Smart Grid operators (DSOs) and the TSO is essential. The TSO, in its function as system manager, can send requests to DSOs in the case of certain situations in the power system (e.g. voltage problems, frequency instability and load flow problems). The DSOs must react to the requests by taking actions in their respective networks and thus delivering supporting services to the TSO, so-called ancillary services. As a result, the TSO receives important ancillary services from DSOs and thus can maintain the system stability and security. This issue is discussed in Section 3.3.

At the same time, distribution networks also need support from the transmission grid. Individual distribution networks do not always have enough resources for a secure, balanced and stable supply (e.g. the ratio of consumption to generation in a distribution network can be larger or smaller than 1 and storage systems are not always available). Therefore, a connection to the transmission system is essential for their operation and for accessing ancillary services. Figure 3.2 shows both the connections between Smart Grids and transmission grid, as well as between Smart Grids.
A Smart Grid consists of the following group of components:

- **Generation systems**: Depending on the type, generators convert energy from one form (e.g. mechanical, potential and kinetic) into electrical energy. Based on the controllability of the power output and the primary energy type (renewable and non-renewable), 3 groups of generators are identified, namely: renewable controllable generators, renewable uncontrollable generators and non-renewable controlled generators.

The controllable renewable generators produce energy from renewable sources and are controllable. Included in this group are for example biogas, hydro, and biomass power plants.

The renewable non-controllable generators produce energy from renewable sources and are not controllable. Photovoltaic and wind turbines are best examples. The power output of the generators of this group is very dependent on uncontrollable characteristics of the primary energy source (in case of wind turbines, these are wind speed, wind fluctuations, wind direction; in the case of photovoltaic systems, these are solar irradiance, the sun position). As a consequence, fluctuations in the power output of these generation systems can be observed.
The non-renewable controllable generators produce energy from non-renewable sources and can be controlled. This group includes coal, gas, oil, nuclear power plants, and cogeneration plants (CHP plants).

In a Smart Grid, mainly generators from the first 2 groups are typically found.

Although belonging to the third group, gas power plants and cogeneration plants could also be used in Smart Grids. The reason lies in their low pollutant emissions (compared to other generators in the third group) and their great benefits for network operation (e.g. high controllability, fast pickup and fast shutdown). Gas power plants are already considered as “ideal bridging technology” for the transition from the fossil-fuelled energy supply towards a regenerative energy supply [34].

It is often claimed that nuclear power plants have a place in Smart Grids, as they have low GHG emissions. However, the argument against this is the unsolved issues of proper storage and disposal of hazardous radioactive waste.

Virtual power plants represent another group of producers. Two types of virtual power plants are to be distinguished.

A virtual power plant type 1 (VPP type 1) represents the combination of several generation plants to form a pool (which may also include storage units and controllable loads). This combination relies on information technology and the virtual power plant is monitored and controlled using a control system. The units composing the virtual power plant can be technologically of different types and are not necessarily installed close together in the same place. By combining the generated schedules of each plant, a desired or predetermined schedule can be selectively driven. **Figure 3.3** illustrates a VPP type 1.
A virtual power plant type 2 (VPP type 2) represents generation plants (such as combined heat and power (CHP) and fuel cells), which are installed in loads (e.g. residential houses, industrial and commercial facilities) and which can feed on request power into the grid. A power supply of a VPP type 2 induces an apparent reduction in the load consumption at the grid connection point of the load. As soon as the power generation is higher than the load consumption, the load turns to an apparent generator. Since it is unsuitable to send a power request signal manually from a control center to each individual load in the grid, load groups are formed. Each load group is assigned a specific power request signal. Once, for example, in the control center the power request signal of a given load group is triggered, the control system automatically sends a request signal to each load of the given load group.

- Consumers: Consumers convert electrical energy into another form of energy (e.g. mechanical, kinetic and light). Thereby the provided electrical energy by generators is consumed. This group includes industrial loads, commercial loads and households. Based on the controllability of the power output (controllable and uncontrollable) and the influence of the consumption (influenceable and
uninfluenceable), 4 categories of loads are distinguished. These are controllable loads, influenceable loads, controllable influenceable loads and non-controllable non-influenceable loads. The power output of controllable loads can be specified by a control system via target values or commands. The consumption behaviour of influenceable loads can be influenced through incentive mechanisms such as energy tariff information.

Besides, a prosumer represents a particular type of consumer which can produce electrical energy through installed generating units such as a PV system on roof, a CHP or a small wind turbine. The produced energy can be self-consumed and/or fed in the power grid.

- Energy storage systems: Energy storage systems store electrical energy and this energy can be withdrawn at a later time. During the charging, depending on the storage technology, a conversion of electrical energy into another form of energy is performed. It could be into mechanical, chemical and thermal and electrical storage [35].

Energy storage systems play a very important role in Smart Grids. They store in the case of energy excess and feed in the event of an energy deficit the stored energy back into the Smart Grid. In addition, these should compensate the power fluctuations of renewable energy plants, so to balance consumption in the event of forecast errors and to resolve some problems in the Smart Grid such as voltage and load flow problems.

- Grid: The grid consists of all interconnected grid equipment (e.g. transformers, overhead lines, cables). Its main function is the transmission and distribution of electrical energy from producers to consumers.

- ICT: This is essential for Smart Grids, as they allow the connection of individual components in Smart Grids. They enable the transmission and exchange of information, data and messages which are necessary and important for the operation of the Smart Grid.

In the planning and implementation of ICT, some factors such as cost, grid topological structure, geographical conditions in the network area, amount of data, data security should be taken into account. In particular, the last two points represent major challenges to be solved urgently. In Subsection 3.2.2, an approach to solve the problem concerning the amount of data will be presented.
Intelligence: The intelligence is necessary for the efficient, optimal, secure, safe, reliable and sustainable management of Smart Grids. The intelligence is based on appropriate and efficient control algorithms. The algorithms have the tasks to run the Smart Grid, to identify potential and actual problems, to solve these problems (automatically or with the support of the control center staff), to assist the control center staff in its work (e.g. by supplying information). These algorithms are installed on the control system and on computer-based systems, so-called “Grid Managers”, and perform the monitoring and control tasks in a Smart Grid.

Grid Managers represent a relevant component for the automation of distribution networks. Such automation would provide advantages such as a reduction of network expansion costs [36, 37] and better network management among others. The installation of measurement devices into Smart Grids is an important addition, since the supervision and control in a Smart Grid cannot be performed without measurements which include measurements in the network and smart metering data at consumer loads.

3.2.2 Structure and operation

Nowadays, the management of distribution networks is performed from control centers. However, this operational control is to a very limited extent, since only very few points in distributions networks are measured. The substations at the medium voltage level are the last information points in distribution networks. After the feeders in these substations, there is very limited information that can enable an inference of the network state. For example, outages and faults in these networks are generally not directly registered in the control center, but are communicated by concerned network consumers via calls to the control center.

Given the changes in distribution networks as mentioned in Chapter 2, it is imperative to seek an increase in the observability of these networks towards monitoring of the entire network state in the control center. For that, much more points in distribution networks should be measured and monitored.

The transmission of all collected information from a distribution network to the control
center, together with its processing, displaying and storage can lead to difficulties due to the enormous amount of data. **Figure 3.4** shows the information flow from the network to the control center. In this figure, the width of the flow lines reflects the amount of information. **Figure 3.5** illustrates the resulting information funnel.

For clarification purposes, the distribution network of the DSO RMN in Darmstadt can be taken as an example. It is a medium sized distribution network, has more than 20 substations and a large medium voltage network including about 4000 local network stations. Each local network station supplies a widespread low voltage network containing from 50 to 250 nodes. Assuming 150 nodes as an average in each local network (low voltage network) supplied by each of the 4000 local network stations, and the 3-phase active power, reactive power, voltage and current values that would have to be transferred regularly to the control center, then one would come to 7.2 million values (3 phase per node x 4 values per phase x 150 nodes per local network x 4000 local networks). In this calculation, the values from the medium voltage network and status information (e.g. switch positions, transformer tap positions) from both the low and medium voltage networks have been omitted. Current control systems cannot handle such a huge number of process information.

In conclusion, a new organization and philosophy for information transmission, processing and storage are imperative.
Figure 3.4 Information flow by the transfer of all information and data from the network to the control center
It is evident from the previous sample calculation that the cost for installing measurement devices and sensors at all network nodes and in all lines throughout the distribution network would be very high and in some cases would be unacceptable. Nevertheless, in order to know the entire network state at any time in the control center, the use of a network state estimation procedure would be necessary. The state estimation method used in transmission systems, mostly based on the WLS method, cannot be implemented easily and only with great effort in distribution systems. The algorithm required an overdetermined system of linear equations. Due to the limited number of measurements in distribution networks, only underdetermined systems of linear equations are obtained. Therefore, a new network state estimation method is urgently needed. This will reflect the network status realistically with only a few measurements, replacement values, pseudo values, load profiles and other data. Such a

Figure 3.5 Information funnel by the transfer of all information and data from the network to the control center
network state estimation method has been developed in this thesis and is presented in Section 6.5.

Due to the expanse of distribution networks, the control center staff cannot solve all individual problems that may occur at the same time or sequentially at different locations in the network. Support for the control center staff can be achieved through automation in distribution networks. A so-called “Grid Manager” (more details are in the following subsections) gets data from the network area for which it is responsible, analyzes these data, identifies potential and actual problems, and solves these problems automatically.

In addition, each Grid Manager transfers some data to its direct superordinate Grid Manager (e.g. status information about the state of the monitored network area, reports of unsolved problems). In this hierarchy, the control system in the control center is the last instance. The relatively small amount of incoming data and information in the control center are manageable and relevant to the work of the control center staff. Hence, an information aggregation and compression process is performed during information transmission from the network to the control center. Figure 3.6 shows the new information flow. In this figure, the width of the flow lines reflects the amount of information. Figure 3.7 illustrates the resulting inverted information funnel.
Figure 3.6 Information flow in the case of the new organisation and philosophy for the transfer of information and data
A Grid Manager is responsible for a network area (e.g. low voltage network, medium voltage network), automatically performs some tasks (e.g. network state estimation, load flow monitoring, voltage profile monitoring) and solves some problems (e.g. overload, voltage limit violations) occurring in its network area of responsibility. If these problems cannot be solved, it turns to its direct superordinate Grid Manager or the SCADA system. Critical issues are reported directly to the control center and will be solved only by the control center staff with the support of tools. Figure 3.8 shows the structure of a Smart Grid with the Grid Managers. A Smart Grid (SG) represents the complete distribution network and consists of Mini Grids.
A Mini Grid (MG) is the feed-in area of a HV/MV substation including the supply transformer and all Micro Grids in the feed-in area.

A Micro Grid (µG) is the feed-in area of a MV/LV local substation including the supply transformer.

![Figure 3.8 Structure of a Smart Grid](image)

The management of a Smart Grid is composed of 3 phases (operational planning phase, operation phase and post-operational phase). The individual phases consist of modules, which in turn consist of 3 essential parts (input, processing and output).

The planning and optimization of the Smart Grid operation in a defined time span (e.g. 24 hours) are performed in the operational planning phase (Figure 3.9). This phase consists of 3 modules:

- **Forecasts**: performing of forecasts (generation, consumption and network condition).
- **Network components operational planning**: checking of the availability of network components for potential use in management and optimization actions.
• Network operation optimization: performing optimization of the network operation based on the results from the modules “Forecasts” and “Network components operational planning”.

**Figure 3.9 Operational planning phase**

During the operational phase (Figure 3.10), the real operation of the Smart Grid within the predefined time span takes place. This phase consists of 3 modules:

• Monitoring: performing a continuous monitoring of the Smart Grid.

• Management and optimization: The results from the module “Monitoring” could lead to management and/or optimization actions on the network (whilst taking into account the results from the operational planning phase), if required.

• Execution and control: The results from the module “Management and optimization” are sent as actions (commands, target values) to the network and executed.
Figure 3.10 Operational phase

The post-operational phase (Figure 3.11) is performed when the predefined time span for the operation of the Smart Grid elapses. Here statistics and evaluations are generated mainly based on both collected information and data during the operational phase as well as information and data obtained during the operational planning phase. The results are important indicators which could deliver hints (e.g. weak network points, problems in the network, necessity of network expansions). Technical indicators can be included in the network planning. Economic indicators can be considered in the investment planning and the asset management.

Figure 3.11 Post-operational phase
3.2.2.1 Structure

In this and the following subsections, the expressions Grid Area (GA) and Grid Manager (GM) are defined as follows. A Grid Area is a generic expression for a Micro Grid (µG), a Mini Grid (MG) or a Smart Grid (SG). A Grid Manager (GM) stands as a generic expression for a Micro Grid Manager (µGM) or a Mini Grid Manager (MGM).

According to the U.S. Department of Energy, a Micro Grid is “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A Micro Grid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.” [38, 39]

The CIGRÉ C6.22 Working Group defines a Micro Grid as “an electricity distribution system containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.” [38]

In this thesis, a Micro Grid (µG) is the feed-in area of a MV/LV local substation including the supply transformer (see Figure 3.8). In a Micro Grid, (almost) all groups of components mentioned in Subsection 3.2.1 can be found. The monitoring and control of a Micro Grid is under the responsibility of a Micro Grid Manager (µGM). This is a computer-based system that is installed in the MV/LV local substation.

A Mini Grid, as defined by UN, World Bank, and NGOs, is “a power system where the produced electricity is fed into a small distribution network that provides a number of end-users with electricity in their premises. Mini Grids are typically off-grid, less than 1 MW in capacity, and utilize diesel, renewable (+battery), or hybrid (combined) fuel sources to produce power. An example of a Mini Grid is rooftop solar plus several devices in a system that generates several thousand watts. As Mini Grids are aggregated and networked, the system becomes more like a Micro Grid, and Smart Grid technology is involved.” [40]

In this thesis, a Mini Grid (MG) is the feed-in area of a HV/MV substation including the supply transformer (see Figure 3.8). In a Mini Grid, (almost) all groups of components (mentioned in Subsection 3.2.1) can be found. The monitoring and control of a Mini
Grid is under the responsibility of a Mini Grid Manager (MGM). A MGM is a computer-based system that is installed in the HV/MV substation.

Algorithms running on a GM allow a widely automated and autonomous mode of operation of the respective GA, and automatic execution of defined tasks.

A Smart Grid (SG) represents the complete distribution network of a DSO and is composed of all Mini Grids in the supply area (see Figure 3.8). The monitoring and management is carried out from a control center using a control system. The control system receives a minimum set of specified information from Grid Managers (such as indicators, recommendations). The information is visualized to the control center staff on the workstation. The control center staff can display each individual GA and have a closer look at the situation in the respective GA. In this case, all the information for the visualization of the grid are directly transmitted once or continuously by the respective Grid Manager to the control system. The visualization allows the control center staff to identify and evaluate the state in the entire Smart Grid, and if necessary, initiate interventions into the grid. Thereby the control center is supported by a variety of algorithms and tools that run on the control system. Depending on the tasks, some algorithms should work and act automatically and others semi-automatically. Automatically operating algorithms perform their tasks autonomously and send their results to the grid (in form of commands, target values). The control center staff can only see the results.

Semi-automatic algorithms perform their tasks autonomously and display the results (as operational recommendations or result variants) to the control center staff. The control center staff must then decide whether the results should be applied and sent to the grid. It may also decide otherwise, discard the results and act itself.

The control system (apart from standard functions available in it and no longer listed here) and each GM should carry out the following functions, among others:

- **gather all measured and sensed data, and information (such as active and reactive power values, voltage values, current values, sensor data) from their respective GAs.**
- **estimate the network state based on the gathered data, load profiles, substitute values and further data.**

Darlus France Mengapche
• evaluate the network state (node voltages, voltage profiles, loading of network components).

• if problems are identified, initiate some adjustment measures:
  o first **network-based measures** such as the adjustment of the tap position of transformers, the adjustment of the reactive power of generators and reactive power compensation units, the switching of the network topology (switching only after evaluation and approval by the control center staff, since automatic switching is typically refused by system operators), the use of operationally permissible tolerance bands [6, 19],
  o then **market-based measures** such as balancing energy, redispatch of conventional generation plants (only those with contractual agreements), redispatch of renewable energy plants (only those with contractual agreements), load management (only those loads with contractual agreements).
  o and at the end **forced adjustment measures** such as redispatch of conventional generation plants (only those without contractual agreements), redispatch of renewable energy plants (only those without contractual agreements), load management (only those loads without contractual agreements).

Here it´s very important to mention that a GM is allowed to perform automatically only **network-based measures** when solving problems. The other 2 measures can be applied by the GM, but executed only after evaluation and approval by the control center staff.

By an optimal use of certain equipment installed in its respective GA, a GM can solve local (i.e. in its respective GA) problems efficiently. If a GM cannot solve a local problem, it sends a message to its hierarchical direct parent GM, whereby the control system at the control center represents the last instance. If the control system cannot solve a problem, it sends a notification to the control center staff.

• perform management tasks (e.g. voltage management, power flow management) and optimization tasks (e.g. power loss reduction) in their respective GAs.

Additionally, a GM should among others:

• receive from its parent GM information (e.g. commands, target values), evaluate and execute these. A GM gets external support from its parent GM in solving
local (i.e. in the GA of the respective GM) problems. For example, in the case of a voltage problem in the GA of the GM, its parent GM can influence the voltage on the primary side of the MV/LV transformer adequately so that the problem becomes solvable.

- receive from the child GMs recommendations (e.g. for external support when solving local problems in respective GAs of its child GMs such as voltage band violation, congestion, faults, critical events), indicators (e.g. status information, group messages, group warning messages, group alarm messages and error type messages from the summary of information received from the GAs of the child GMs). These are then evaluated and executed.

- receive from the control system in the control center information such as target values, commands, updated topology information in the control center after switch position changes of not monitored switching devices in the GA of the respective GM, configuration data and parameterization data. These are then evaluated and executed. The GM gets external support from the control system in solving local problems in its respective GA.

- send to the parent GM or the control system (in case that the control system is its parent instance) recommendations (e.g. for external support when solving local problems in its respective GA such as voltage band violation, congestion, faults, critical events), indicators (e.g. status information, group messages, group warning messages, group alarm messages and error type messages from the summary of information received from its respective GA).

- send to the child GMs information (e.g. commands, target values). The GM supports its child GMs in solving local problems in their respective GAs. For example, in the case of a voltage problem in the GA of one of its child GM, the GM can influence the voltage on the primary side of the MV/LV transformer adequately so that the problem becomes solvable.

- send to the control system in the control center updated topology information after switch position changes of remote-controlled switching devices in its respective GA, information about faults, critical events and recommendations (e.g. for external support when solving local problems in its respective GA if actions requiring the intervention of the control center staff should be performed). For visualizing the GA of the respective GM in the control center,
the GM could transfer once after request from the control center or continuously all information from its respective GA to the control system.

3.2.2.2 Operation

a Operational planning phase

The execution of the individual modules of the operational planning phase is not done by the GMs, but only in the control center. The GMs only receive from the control center the list of all ready for operation components that could be used for any management and optimization actions in their respective GAs during the operational phase.

The operational planning phase, carried out in the control center, consists of the modules “Forecasts”, “Network components operational planning” and “Network operation optimization”.

The module “Forecasts”:

- needs in the input part:
  - Time horizon (e.g. 24, 48, 72 hours).
  - Network topology.
  - Network data (e.g. line data).
  - Power schedules of:
    - controllable power plants and market storage units.
    - virtual power plants (aggregated and disaggregated).
    - renewable energy plants (generation forecasts).
    - schedulable loads.
    - other loads (aggregated and disaggregated) from pseudo data, consumer load profiles, from forecasts based on historical consumption data collected from smart meters.
  - Information about planned network events (such as switching, construction measures, maintenance and repair), locations and times.

- performs in the processing part:
Execution of network state forecasts (e.g. through load flow calculations).

Analysis of results.

Storage of encountered problems and their occurrence times.

Generation of a list of planned network events (such as switching, construction measures, maintenance and repair in the distribution network) with locations and times.

Storage of results/outputs.

- gives in the output part:
  - Voltage values at network nodes.
  - Power flow data (P, Q) in the network.
  - Network topology.
  - Active and reactive power demand from the upstream network level.
  - Power schedules of:
    - controllable power plants and market storage units.
    - virtual power plants (aggregated and disaggregated).
    - renewable energy plants (generation forecasts).
    - schedulable loads.
    - other loads (aggregated and disaggregated) from pseudo data, consumer load profiles, from forecasts based on historical consumption data collected from smart meters.
  - Indicators on the network transmission capacity.
  - Indicators on inadmissible/critical situations (voltage limit violations, component overloads and other possible problems).

- A list of planned network events (such as switchings, construction measures, maintenance and repair work in the distribution network).

The module “Network components operational planning”:

- needs in the input part:
  - Technical data of connected power generation systems (e.g. Pmin, Pmax, Qmin, Qmax, indicators on the type and range of services).
  - Information about network regulating equipment (e.g. type, network connection points, ratings).

- performs in the processing part:
 mín the generación of a list of all controllable power generation plants in the network (power plants, market storages) including their contractual terms of use and technical capabilities.

- Generation of a list of all controllable loads in the network including their contractual terms of use and technical capabilities.

- Generation of a list of all network regulating equipment such as step and variable transformers, phase shifters, network storages, reactive power compensation units (e.g. shunt reactors, capacitor banks, FACTS).

- Checking of the availability of the listed plants and components.

- Generation of a list of all ready for use plants and equipment per GA.

- Storage of results/outputs.

  gives in the output part:

- List of all controllable power generation systems in the network (power plants, market storages) including their contractual terms of use and technical capabilities.

- List of all controllable loads in the network including their contractual terms of use and technical capabilities.

- List of all network regulating equipment such as step and variable transformers, phase shifters, network storages, reactive power compensation units (e.g. shunt reactors, capacitor banks, FACTS).

- List of all ready for use plants and equipment.

The module “Network operation optimization”:

  needs in the input part:

- Output from the module “Forecast”.

- Output from the module “Network components operational planning”.

- Frameworks (technical, economic and regulatory).

- Voltage and frequency dependency factors of Mini Grids and Micro Grids (pseudo data or computed data by μGMs and MGMs from collected historical measurements).

  performs in the processing part:

- Preventive execution of V-PQ management:
  - Reactive power management for optimizing the reactive power demand in the distribution network.
- Voltage management (including voltage stability analysis) in case of possible voltage problems.
  - Preventive execution in case of problems related to network capacity [41]:
    - first of *network-based measures* such as tap position change of transformers, reactive power adjustments at generators and reactive power compensation units, switchings of the network topology,
    - then of *market-based measures* such as balancing energy, redispatch of conventional generation plants (only those with contractual agreements), redispatch of renewable energy plants (only those with contractual agreements), load management (only those loads with contractual agreements),
    - and at the end of *forced adjustment measures* such as redispatch of conventional generation plants (only those without contractual agreements), redispatch of renewable energy plants (only those without contractual agreements), load management (only those loads without contractual agreements).
  - Determination of the extent (duration, power, costs) for preventive V-PQ management per plant/component used and in total.
  - Determination of the extent (duration, power, costs) for the preventive network-based and market-based measures per plant/component used and in total.
  - Generation of a list of possible preventive adjustments in the context of network management.
  - Storage of results/outputs.
- gives in the *output* part:
  - List of interventions from the execution of preventive V-PQ management separately for each GA.
  - List of interventions from the execution of preventive network-based and market-based measures separately for each GA.
  - Indicators on the possible:
    - extent (duration, power, costs) for the execution of preventive V-PQ management per plant/component used and in total.
extent (duration, power, costs) for the execution of preventive network-based and market-based measures per plant/component used and in total.

b Operational phase

As already mentioned, the operational phase consists of the modules “Monitoring”, “Management and optimization” and “Execution and control”. The execution of the individual modules is done by each GM and the control system.

The module “Monitoring”:

- needs in the input part:
  - Network topology (only the respective GA).
  - Network data (e.g. line data).
  - Technical Frameworks.
  - Pseudo data.
  - Measured values (P, Q, V, I, branch power flow), messages and sensor data from the respective GA.
  - Information from child GMs such as indicators, recommendations.
  - Information from the parent GM or the control system (in case that the control system is the parent instance) to a given child GM such as commands, target values.
  - Information from the control system to GMs such as updated topology data, configuration data and parameterization data.
  - Information from the control center staff to the control system such as commands, target values, updated topology data, configuration data and parameterization data.

- performs in the processing part:
  - Receiving and analyzing of information from the respective GA.
  - Receiving and analyzing of information from child GMs.
  - Receiving and analyzing of information from the parent GM or the control system (in case that the control system is the parent instance).
  - Receiving and analyzing of information from the control center staff to the control system.
- Estimation of the GA state.
- Monitoring of the voltage profile and the loading of network components
- Aggregation of information from the GA to information units, so-called GA state indicators.
- Computation, determination and storage of technical factors such as the number of problems per type, the occurrence locations of the problems, the component outage frequency, component reliability.
- Computation, determination and storage of economic factors such as the loss costs, the costs of performed actions (management and optimization actions) from the perspective of network operations (expenses, income, savings) and more.
- Sending of information to the parent GM or the control system (in case that the control system is the parent instance) such as GA state indicators.
- Sending of information directly to the control system in the control center, if critical situations occur such as outage of components, critical faults.
- gives in the output part:
  - Information about the state of the GA, schedule profiles (P, Q, V, power factor), resource utilization.
  - Aggregated information from the GA to information units, so-called GA state indicators.
  - Technical and economic factors.
  - Information for the respective parent GM.
  - Information for the control system.
  - Information for the control center staff.

The module “Management and optimization”:
- needs in the input part:
  - List of all available components that could be used for any management and optimization actions in the GA during the operational phase.
  - Input and output from the module “Monitoring”.
  - Output from the module “Network operation optimization” of the operational planning phase.
performs in the processing part:

- Checking of the necessity and the validity of the generated adjustments from the module “Network operation optimization” with respect to the current network conditions.
- Execution of voltage/active power/reactive power management (V-PQ management):
  - Reactive power management for optimizing reactive power demand in GA.
  - Voltage management (including voltage stability test) in case of possible voltage problems.
- Execution in case of power flow and congestion management [41]:
  - first of network-based measures,
  - then of market-based measures,
  - and at the end of forced adjustment measures.

As mentioned earlier, a GM is allowed to perform automatically only network-based measures when solving problems. The other 2 measures can be applied by the GM, but executed only after evaluation and approval by the control center staff.

- Execution of power schedule management rather than energy management (details in Section 3.3).
- Execution of a network-based power loss optimization.
- Transmission of information to child GMs if support was requested by these child GMs or if help from these child GMs for supporting the respective parent GM is required.
- Transmission of information to its respective parent GM if a GM needs support to solve local problems.
- Transmission of information to the control system and notification to the control center staff if problems in a GA cannot be solved neither by the respective GM of that GA nor after support from the parent GM or the control system.
- Determination of the efforts (duration, power, costs) for a V-PQ management per used plant and in total.
o Determination of the extent (duration, power, costs) for the different types of measures (network-based, market-based and forced) per used plant and in total.

o Generation of the list of adjustments to be performed during the network management.

o Storage of results and outputs

- gives in the output part:
  o List of interventions for the execution of V-PQ management separately for each GA.
  o List of interventions for the execution of network-based, market-based and forced measures separately for each GA.
  o Indicators on the possible:
    - extent (duration, power, costs) for the execution of V-PQ management per plant/component used and in total.
    - extent (duration, power, costs) for the execution of network-based, market-based and forced measures per plant/component used and in total.
  o Information (e.g. target values, commands) and schedules for the execution of management and optimization actions. Hereby child GMs may be involved by being asked to make adjustments in their respective GAs.
  o Information to the respective parent GM or the control system (in case that the control system is the parent instance).
  o Information to the child GMs
  o Information to the control system and control center staff.
  o Information from the control system to GMs.

The module “Execution and control”:

- needs in the input part:
  o Output from the module “Management and optimization”.

- performs in the processing part:
  o Execution of information from the module “Management and optimization” in the respective GA.
o Computation and determination of technical factors such as the adjustment frequency of transformer taps and more.

o Computation and determination of economic factors.

o Storage of these factors on the respective control and management instance, i.e. GM or control system.

o Transmission of information to its respective parent GM if a child GM needs support to solve local problems.

o Transmission of information to child GMs if support was requested by these child GMs or if help from these child GMs for supporting the respective parent GM is required.

o Transmission of information to the control system and notification to the control center staff if problems in a GA cannot be solved neither by the respective GM of that GA nor after support from the parent GM or the control system.

• gives in the output part:
  o Information (e.g. targets, commands) to the GA.
  o Information to the respective parent GM or the control system (in case that the control system is the parent instance).
  o Information to the child GMs.
  o Information to the control system and the control center staff.
  o Information from the control system to the GMs.
  o Technical and economic factors.

c Post-operational phase

At the end of the predefined time span for the operation of the Smart Grid, the post-operational phase conducts a technically and economically statistical evaluation. The module “Statistics”:

• needs in the input part:
  o Technical and economic factors from the „Operational phase”.

• performs in the processing part:
  o Generation of technical and economic indicators.
  o Transmission of the indicators by the GMs to the control system once a day or after request from the control center.
o Reception by the control system of all transmitted indicators from all GMs.

- Storage of all technical and economic indicators on the control system in the control center.
  - gives in the output part:
    - All technical and economic indicators.

### 3.3 Possible new ancillary services

According to the transmission code [6] and the distribution code [19], “ancillary services in the electricity supply refers to the services indispensable to the proper functioning of the system which system operators provide for connection owners/connection users in addition to the transmission and distribution of electrical energy, and which thus determine the quality of power supply”. These are:

- frequency control,
- network restoration,
- voltage control and
- system/network operational management.

TSOs perform all 4 types of services in their respective transmission grids. DSOs perform only the 2 last in their respective distribution grids and also the second type under the supervision and guidance of their respective TSOs.

For the provision of ancillary services, network operators can use own or third-party (according to agreement with owners) network components. Network operators can also receive the necessary ancillary services from suppliers/providers against payment of agreed contractual remunerations [6, 19]. Given the large number of installed components in Smart Grids, DSOs would in the future have a much greater possibility to provide their ancillary services. They can make use of own or third-party network components, or of the large number of possible suppliers/providers in the Smart Grid. In some cases, DSOs could also request support from TSOs.

In contrast, TSOs will in the future not be able to fully provide their ancillary services due to the changes in transmission networks as described in Chapter 2. For example, in
the future the voltage control in the transmission network could not be effectively performed due to lack of reactive power capacity which is nowadays provided by large power plants. Another example is the network restoration, which is nowadays performed under the co-ordination of TSOs with the involvement of mainly large power plants. The lack of these large central power plants in the future is a major issue, and Smart Grids can precisely at this stage play a crucial and important role. DSOs thus have the opportunity to play the role of providers of ancillary services to TSOs and gain revenue for this activity. This consideration can be supported with the following argumentation:

A TSO is responsible for the system management of its control area. Although the transmission grid and Smart Grids are in its control area, the TSO is only responsible for the operation of the transmission network. DSOs are on their side responsible for the management of their Smart Grids. In case of problems in the control area, a TSO should not perform direct adjustments on components within Smart Grids. Such an action represents an intervention in the operational management of the Smart Grids. This intervention could cause unwanted problems, disturbances and side effects in Smart Grids. In addition, due to the high number of components in Smart Grids, a TSO cannot exactly determine the adjustments to carry out in Smart Grids in order to efficiently and optimally solve its problems. Therefore, in future the DSO will have to be responsible for new ancillary services.

Crucial for solving problems in a transmission system are the feed-ins and withdrawals at its nodes. Problems can be solved by adjusting the powers at its nodes. From the perspective of a TSO, Smart Grids can be viewed as active components at the transmission system (Figure 3.12). These can offer and delivery ancillary services to the transmission system. After receiving a request from the TSO, a DSO should take appropriate, necessary and effective measures in its Smart Grid to meet the request without causing any dangers and disturbances in its own network. Thereby it can adjust own and third-party components. It can also send requests to several potential suppliers of ancillary services within its Smart Grid. These suppliers in the Smart Grid are remunerated by the DSO. The DSO in turn is remunerated by the TSO.
For the following considerations, a Smart Grid acts from the perspective of the transmission network at which it is connected as an active component. Therefore, the delivery of the following ancillary services by a Smart Grid to a transmission network is possible:

- Voltage management

  In case of detection during the network operational planning or in case of occurrence during the operational system management of voltage problems in the transmission network due for example to a deficit or an excess of reactive power, a TSO can request a DSO to adjust to predetermined values and maintain the reactive power exchanges at selected connection points between the transmission system and the Smart Grid. Then, the DSO reacts to the request with appropriate and efficient actions for reactive power adjustment in its Smart Grid in order to influence the reactive power exchanges at the selected connection points. These actions include the reactive power adjustments of generators, loads and reactive power compensation units, as well as tap position adjustments of the transformers supplying the Smart Grid. A network topology change can, if necessary, also be carried out. During all these measures, no dangers and disturbances should occur in the Smart Grid.
Power flow management
In case of detection during the network operational planning or in case of occurrence during the operational system management of congestions and unwanted powers flows in the transmission system, a TSO can request a DSO to adjust to predetermined values and maintain the active and/or reactive power exchanges at selected connection points between the transmission system and the Smart Grid. Then, the DSO reacts to the request with appropriate and efficient actions for power adjustment in its Smart Grid in order to influence the power exchanges. These actions include the power adjustments of generators, loads, reactive power compensation units and the tap position adjustment of the transformers supplying the Smart Grid. A network topology change can, if necessary, also be carried out. During all these measures, no dangerous situations and disturbances should occur in the Smart Grid.

Power schedule management rather than energy management
It is often mentioned that energy management in a Smart Grid is to be performed by DSOs. The VDI guideline 4602 defines the “energy management as the forward-looking, organized and systematic coordination of procurement, conversion, distribution and use of energy to meet the requirements, taking into account environmental and economic objectives” [42]. In other words, this means the prediction of consumption and production in the Smart Grid, and the execution of energy transactions (purchase of lacking energy on the energy stock exchange, from power plants, from controllable loads) to cover the residual load. It can be extracted from the definition that the energy suppliers are responsible for this task, but not the network operators. As already mentioned in Section 2.3, a network operator can not accomplish this task due to its monopoly position. A network operator should basically only concentrate on the \textit{KW tasks} (power tasks such as power flow management, loss management) and not on the \textit{KWh tasks} (energy tasks such as energy transactions on energy stock exchanges, purchase of energy from power plants). In Germany, this role separation is reinforced by the key issue paper “Smart Grid and Smart Market” of the Federal Network Agency [43]. In summary, a network operator is therefore not allowed to perform energy management, but power schedule management. The power schedule management deals with holding the power schedule (active and reactive power exchange) through the DSO at all connection points between
its Smart Grid and the transmission system. This task is performed by the DSO on behalf of suppliers in its network area, since the DSO alone can and is allowed to intervene in the grid operation. The suppliers do not have this possibility and authorization. Therefore, the DSO can detect power deviations from the schedule and balance these in order to avoid the use of expensive balancing energy from the transmission system. Power deviations from the schedule might be due for example to weather dependency and forecast uncertainties. In case of deviations, the DSO can activate positive or negative power from prequalified units directly connected to the Smart Grid, having contractual agreements with the DSO and, selected in advance according to a transparent and non-discriminatory procedure. These units could be conventional generation plants, renewable energy plants, loads, storage units and aggregated loads and/or generation plants. For this service, these units are compensated by the DSO. The DSO in turn sends an invoice to the identified suppliers which caused the schedule deviation. It must be mentioned that this invoice could be less than the invoice issued for the use of balancing power from the transmission system.

The exact determination of the causers of schedule deviations requires the knowledge of the grid state (e.g. using a network state estimator as described in Section 6.5) and a determination of the causer-fair power flow tracing in the network (will be described in Section 6.3).

- Network restoration

In the future it will be even more difficult or impossible to perform a network restoration with only the few remaining systemically relevant and controllable power plants in the transmission network (as already mentioned in Subsection 2.4.2.4). Smart Grids can make a major contribution to solving this problem.

A network restoration approach could look as follow: Suppose there is a supply breakdown (Figure 3.13). Based on a consumption forecast, a generation forecast of all non-controllable generation plants and a determination of the power capacity of all controllable generation plants in each Smart Grid connected to the transmission system, a stable partial supply (in case that the total production is less than the total consumption in the Smart Grid) or a stable full supply (in case that the total production exceeds the total consumption in the Smart Grid) can be restored in each Smart Grid. The same step is done in the
transmission network using the connected generation units and loads (Figure 3.14). As a next step, the Smart Grids are successively connected to the transmission network for the restoration of a system partial supply (Figure 3.15). For the further coordination of the network restoration, the TSO receives from the various Smart Grids information about the current generation capacity still available and the power demand forecast to supply unsupplied loads. With this information and with the support of neighbouring TSOs, of generation units and loads connected to the transmission network, the TSO can continue the network restoration (Figure 3.16). By this way, a network restoration can be done quickly and efficiently. It´s important to mention that during this operation, the synchronization conditions should always be checked and these should be fulfilled before performing switching operations.
Figure 3.13 Supply breakdown

Figure 3.14 Local restoration of supply
Figure 3.15 Reconnection of Smart Grids to the transmission grid and partial supply

Figure 3.16 Full supply in the whole system
The other ancillary services mentioned in **Subsection 2.4.2** as:

- substitution of the rotating mass,
- compensation energy (primary, secondary and tertiary control)

are offered by producers, consumers and virtual power plants having a pre-qualification agreement for these services through a transparent platform (e.g. market place). In the case that the power for providing these ancillary services is requested and activated, the DSO in whose network the plants are connected, must always maintaining sufficient network capacity.

### 3.4 Security and ICT

In the design and implementation of control systems in the past, the focus was more set on the robustness, performance and the speed of these systems. The security aspect played a rather minor role. With the increased networking of SCADA systems with other systems via networks to achieve added value, an increase of attacks and attempted attacks on these systems could be observed. For the attacks, the vulnerability and the big security gaps were exploited. For example, an attack from the Internet on a water pump in the US was reported [44]. As part of an experiment, the municipal utility in Ettlingen (Stadtwerke Ettlingen) tested the security of their SCADA system and failed at the end. The commissioned hacker could infiltrate the system [45]. From these examples among many others, it can be deduced that the current control systems are not secure enough against cyber attacks.

Strict, rigid, secure and reliable concepts and guidelines for the security of information and communication infrastructures used for monitoring and controlling critical supply infrastructure such as electrical grids are urgently needed.

Nowadays a variety of technological media for the transmission of data and information is available. Most of these media are in use since couple of years, experience has been gained with these and some are well proven. The transmission of data and information can be performed by wire (e.g. LAN, powerline, fiber optics) or wireless (e.g. GPS, GPRS, UMTS). The selection and use of a medium should be well thought, considered very carefully and decided depending on certain factors such as geographic conditions in the network area, technical operating requirements and financial requirements.
Currently both standardized (e.g. IEC 61850, IEC 60870-5 [46]) as well as proprietary (by system and equipment manufacturers) protocols are available. However, the networking of systems and components from different vendors in Smart Grids by means of information technology requires in advance the use of a common communication protocol (i.e. the same communication and interaction language) to enhance interoperability among these systems and components. Therefore, standardization of a communication protocol for Smart Grids is required. The development of such a protocol should be done within a framework involving standardization bodies, system and device manufacturers, and, system and device users. Once a standardized protocol is ready, the implementation can be done by system and device manufacturers either:

- directly on their systems and devices, if technically feasible and economically reasonable, or
- in a first step through the use of a protocol converter between the standardized protocol and proprietary protocol on their systems and devices, if technical and economic conditions are not met at the transition time. Then the next goal should be to equip the next generation of these systems and devices with the standardized protocol.

At the moment, intensive works are underway on the Standard 61850 for use in Smart Grids. This standard describes a general communication protocol for the protection and control [47]. An experimental use for:

- network monitoring and automation,
- aggregation of producers, loads and storages,
- smart metering

already took place with successful outcomes in the pilot project Web2Energy [48] within a part of the distribution network of the DSO RMN [49].

3.5 Complex tasks and Training needs

The previous sections have shown that the management of distribution networks in the future will be more complex than ever before. The DSOs will be responsible for
numerous additional tasks in the framework of network management and will provide some new important ancillary services to the TSOs. A part of these tasks will be performed by the autonomous Grid Managers and the control system. As a result, many advantages such as workload minimization of the control center staff and efficient network operation will be achieved. However the control center staff should not withdraw completely from the network operation, it should not completely rely on the systems (Grid Manager and control system) and should not give full control to these systems. The control center staff should be able to understand the actions of these systems on the network and the impact of these actions on the network. Additionally, the control center staff should have a good understanding of the conditions and interactions in the network. It should be able to interpret and understand the information provided by the systems. All of this is important because the control center staff must, in case of faults or malfunctions of for example Grid Managers, take over the network operation manually. Therefore, training of the control center staff and its preparation for all new tasks and new challenges in the management of distribution networks in the future are necessary and indispensable. The next chapter deals with the topic of training of the control center staff.

3.6 Summary

Smart Grids represent distribution networks of the future. The fundamental difference from current distribution networks lies in the implementation of automation (introduced by ICT and intelligence) in Smart Grids. Apart from that, Smart Grids contain conventional components present in current distribution networks (e.g. loads, network component) and some new components such as generators, energy storages and virtual power plants. A Smart Grid (SG) represents the complete distribution network and consists of Mini Grids. A Mini Grid (MG) is the feed-in area of a HV/MV substation including the supply transformer and consists of all Micro Grids in the feed-in area. A Micro Grid (μG) is the feed-in area of a MV/LV local substation including the supply transformer.

The transmission of all collected information from a distribution network to the control center, its processing, displaying and storage do not always make sense and is not
recommended due to the huge amount of data generated during the operation of Smart Grids.

In addition, such action would cause a great strain on the control center staff (for the interpretation and evaluation of extensive information) and could also probably lead to some technical problems (e.g. possible congestion of the control system and communication infrastructures, slowness of data processing and problems with data synchronization). Therefore, a new organization and a new philosophy for information transmission, processing and storage are necessary. This requires the use of a Grid Managers, which will be responsible for the acquisition, processing of data from their respective monitored network areas (e.g. Mini Grid, Micro Grid).

The possible operational management of a Smart Grid has been described in this chapter. It consists of 3 phases (operational planning phase, operational phase, post-operational phase). The individual phases are composed of modules, which in turn consist of 3 essential parts (input, processing and output).

The mentioned changes in transmission networks (in Chapter 2) lead to the fact that TSOs will in the future no more be able to fully provide some ancillary services (e.g. voltage control, network restoration). DSOs on the other hand will have more potential to offer and provide ancillary services such as voltage management, power flow management, power schedule management and network restoration to TSOs.

The integration of ICT in distribution networks must meet strict, rigid, secure and reliable security concepts, guidelines and laws. This is important due to the threats of attacks with devastating consequences on the electrical power supply. Moreover, the standardization of communication protocols for the networking of components from different manufacturers is essential. This enables the easy integration, interchange and interaction of these components in the Smart Grid independently of their manufacturers. Since the control center staff must still remain at the center of the network operational management and, due to its new responsibilities and the new complex tasks in the operational management of Smart Grids, there is an urgent need to prepare and train the staff.
Chapter 4  Training of the DSO Control Center Staff

4.1  Introduction

In Chapter 3, it was stated that a transformation of current distribution networks into Smart Grids is necessary. This transformation induces complex tasks in network operational management. Despite the automation of distribution networks, the control center staff must still remain at the center of the network operational management. It must be able to interpret and understand the network situations, to know most of the possible problems which could occur, to know their causes and solution possibilities. This requires a training of the control center staff.

In Section 4.2, the necessity for training of the control center staff is presented. Various training methods are presented and described in Section 4.3. In Section 4.4, the training evaluation is addressed.

4.2  Necessity of training

According to [6, 19], the network operator must ensure that the control center staff is trained regularly. However, reality shows that network operators do not always perform regular training of their control center staff despite recommendations and obligations to do so. A survey performed by the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da) some years ago (based on questionnaires related to training and completed by network operators) reveals that apart from the positive answers (55%) on the importance of training control center staff, the reasons/arguments mentioned for not carrying out training included:

- It is expensive.
- It takes a lot of time.
- As no problems have occurred to date, it is not necessary.
- It is laborious (due to data entry and data management).
- Why should my staff be trained if other network operators do not do the same?
4.2.1 Training requirements of control center staff

Training of the control center staff is important for the following reasons:

- It creates greater certainty and increases self-confidence. The control center staff is sure of what needs to be done and complete tasks correctly without fear of having to prove or defend themselves and take greater responsibility.
- It improves knowledge.
- It enhances motivation.
- It allows for greater understanding of grid behaviour.
- It allows quick and appropriate reaction. The control center staff should be able to locate faults, properly assess the situation and then take correct and efficient decisions. They should be able to act correctly, accurately, quickly and safely during troubleshooting.
- It prepares staff for different types of scenarios (usual and unusual situations).
- It prepares staff to handle tools for operational management.
- It allows for training of procedures in normal situations (e.g. for avoidance and reduction of bad/wrong decisions).
- It allows for training of procedures in fault situations (e.g. for avoidance and reduction of bad/wrong decisions and mistakes which could extend a problem or which could lead to additional problems, for efficient possible solutions and approaches).
- It allows staff to train in coping with stressful situations.
- It allows staff to be up to date to the latest technical and regulatory frameworks, and their evolution.
- It helps to meet and overcome the challenges encountered in the grid.
- It generates new ideas and brings improvements of existing processes.

4.2.2 Training benefits for network operators

Some benefits for network operators arising from a training of their control center staff are as follows:

- Training of control center staff contributes to the economic success of the company. Good training pays in efficient operational management and reduction
of bad/wrong decisions causing faults and increasing costs. The know-how of
the employees (acquired, maintained and refreshed through training) is a great
asset for the company.

- Network operators can prove that they are meeting their obligations in terms of
regular training of its control center staff [6, 19]. In Germany and some other
countries, regular training of the control center staff is mandatory. In the event
of grid outages or problems, the regulator asks for details on how the emergency
was managed. Possible financial losses and penalties can be encountered by the
company if incorrect operations, inadequate training or missed maintenance are
identified. Regular training provides the network operator a good basis in case of
litigation.

- Training strengthens the commitment of the control center staff to remain in the
company and to contribute to the fulfilment of established goals of the company.

- On the social level, training gives a good image to the company due to the
resulting low number of bad/wrong operational decisions and the fast and
professional reaction of staff in the event of faults and other problems. This
leads to higher satisfaction of consumers.

4.3 Training methods

Various methods for training the control center staff in the deregulated market exist.
Some important examples were presented and explained in [50]. These are:

- Know-how transfer from experienced employees.
- Internal and external training events.
- Training of network restoration strategies.
- Business games.
- Use of training simulators (online, offline).

Depending on the training goals to be achieved, each of these methods has its own
strengths and weaknesses. Therefore a well-thought out and careful selection method is
of great importance for training success. Each method will be presented briefly in the
following subsections.
4.3.1 Know-how transfer from experienced employees

In this method, an experienced employee plays the role of instructor and shares his/her knowledge with the trainee. This knowledge transfer can take place during work (shift). The instructor discusses the topics with the trainee, shows examples and gives explanations. Thereby the trainee has mainly a passive role (listener and viewer), observes his/her instructor at work and learns in this way.

Strengths:
- Easy and widely used method.
- No additional organizational effort, since the knowledge transfer happens during the shift.

Weaknesses:
- The training quality depends heavily on the experience, knowledge, teaching skills and teaching quality of the instructor.
- The decision-making in situations cannot be properly developed by the trainee.
- The trainee cannot build properly his/her own experience since he cannot experience itself in certain situations.
- The coping with stress (e.g. in critical situations) cannot be practiced properly by the trainee.
- The training of various scenarios cannot be practiced because the discussed cases do not always occur during the shift. If an event occurs, then the instructor must handle it and the trainee observes only. Often in such situations there is little time for knowledge transfer or the information transferred is limited.

4.3.2 Internal and external training events

During training events, a topic specified by the organizer is presented. The training can be offered internally (by the host company) or externally by an organizer.
Strengths:

- The organization of internal training events by the company department responsible for example for network protection, network planning, research and development is simple and usually inexpensive.
- Free discussion without internal company dependency and interests.
- The instructor knows different solutions and can take a broad view.
- The instructor can also give suggestions for daily network operations.

Weaknesses:

- The topics of external training events are generally specified by the organizer (e.g. network protection, switching operation). The instructor treats and focuses exclusively on the specified topic.
- This method is suitable for familiarization with and advanced education in specific topics.

4.3.3 Training of network restoration strategies

Here the trainee receives from the instructor a disturbance event with an assumed system state and corresponding load and weather conditions. The trainee should determine the expected switching state after the event occurrence and the impact of the event on the network. The trainee should develop the necessary measures for troubleshooting and, if necessary, the strategies for network restoration. For the fulfilment of the task, he/she has plenty of time (e.g. few days to weeks) and all resources to gather information (e.g. calculation tools, books). At the end, the trainee should present the results to the instructor and/or his/her colleagues and this is followed by a discussion.

Strengths:

- Very effective.
- The trainee can intensively deal with the problem.
- Good suggestions for adaptations and improvements of for example a number of operational regulations and also of the normal switching state of the network may sometimes arise from the discussion.
Weaknesses:

- No training of stressful situations.
- The lack of dynamic in the training is characterized by the fact that the extracted results from calculation programs are static (static values at a given time). However, the dynamic events and effects (e.g. protection reactions) in the real network are not experienced by the trainee.
- There is a lack of uniformity since during group training, individuals could work on a separate topic and present it. As consequence, the quality of results is subjective.
- There are discontinuities in the long elaboration time due to the trainee's further activities (e.g. shift, family, free time and holidays). These discontinuities have different effects on the results and the development of experience.
- The consultations with the instructor could take place after a long time period.
- Lengthy involvement with one specific topic.

4.3.4 Simulation games

This method allows the training of the interaction and the coordinated approach of several control instances involved in network operational management. The training is done as in reality, i.e. the instances (participants) do not sit at the same table, they communicate by phone, some participants drive to stations to simulate switching orders (local switching of not remotely controllable switching devices) followed by updates of topology information in the control center.

Strengths:

- It is suitable for training of various control instances involved in network operational management.
- Communication, interaction and coordinated approach are practiced.

Weaknesses:

- Different variants for the evaluation of intermediate states must be computed in advance of the training.
- Unrealistic atmosphere.
The method does not focus on the training of individual staff members on specific topics.

### 4.3.5 Use of training simulators

A dynamic training simulator is a computer software system which can simulate electrical power networks. One can distinguish between online and offline training simulators.

An online simulator is connected via a SCADA system to the process and obtains live data to calculate the network state. All interventions of the trainee (target values, commands) are not sent to the process, but to the simulator which then computes all network reactions.

An offline training simulator is totally decoupled from the process and computes the network state based on predefined stored information. To produce some dynamics (as observed in reality), all generators and loads are given power schedules. Even in the case of no intervention from a human, the network is “alive” because of generator changes, load changes and changes initiated by controllers. The trainee has all the same possibilities as in an online training simulator. The simulation can be done with an artificial network model or a real network model (e.g. model of the operator’s network).

If the training is done with a real network model, the following strengths and weaknesses arise:

**Strengths:**

- Dynamic training is possible, since reactions from among others switching operations, sending of target values and sending of commands are directly visible. Some simulators react in real time.
- High compliance with reality.
- Training of interactions and workflows (e.g. switching operations followed by updates of topology information in the control center) is possible.
- Training of the behaviour of various equipment and technologies is possible.
- Intervention of the instructor over the trainer interface to influence the network (setting faults, setting disturbances) is always possible and the training of the trainee’s reaction followed directly by a discussion with the instructor is given.
• Training of different scenarios and topics in a short time is possible.
• Recurrent training on network operator’s own network is feasible.
• The decision-taking in situations by the trainee can be practiced.
• The trainee can build his/her own experience properly because he/she can experience situations and influence the network state with own decisions.
• The trainee can train how to deal with and manage stress.
• Risk-free training is possible because the training has no effect on the real network. The trainee can experience network fault cases and their consequences, and learn from that.
• During the shift, a control center staff member can define his/her own scenarios on the training simulator and train. From this, new knowledge and findings could arise, and these can be shared and discussed with colleagues. These new facts can be inserted in a reference manual.

Weaknesses:

• This method requires a unique effort in data collection and data entry for building the network data model (e.g. generator and load schedules, parameters of protection devices and controllers, equipment data such as line length, line resistance and configuration of stations). If the control system and the simulator are from the same manufacturer, the data model of the simulator can be generated in some cases automatically from that of the control system. Then, if required, some additional specific data for the simulator should be entered.
• Continuous maintenance of the data model is required. The data model of the network simulator needs to be updated in case of changes in the network structure (including the integration of new equipment, network expansion) and of protection parameters. If available and possible, data model updates can be performed automatically.

A comparison of the different training methods shows that a training with a simulator leads to a compensation of almost all the weaknesses of the other methods and has the same advantages as these other methods. This method has additional advantages. Despite its weaknesses (which can be compensated by applying the measures described above), the strengths outweigh greatly. Given this fact and, given the identified challenges and requirements (Chapter 2 and Chapter 3) in future distribution

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networks, the training with a training simulator is chosen as the method for training control center staff. This method is considered in further sections of this thesis.

### 4.4 Training evaluation

Evaluation plays a very important role in the context of training. It enables control/check of the learning achievement of the training [51] and should be objective. For that, clear and consistent criteria, which are generally valid in the training context, must be established. A distinction is made between the evaluation of the training process and the evaluation of the trainees.

The results of an evaluation of the training process can be used as feedback to improve, adjust and optimize the training scenarios and the training system (including system operation, system performance, network component models, functionalities). In this iterative process, the training improves over time. The following criteria can be applied for the evaluation:

- Reaction and reliability of the training system.
- Closeness to reality of component models and behaviours, and of the network behaviour.
- Clarity and ease of operation and visualization.
- User-friendliness.
- Clarity and completeness of the training scenarios.
- Degree of difficulty and contextual coherence of the training scenarios.
- Feasibility of training scenarios.

The results of an evaluation of the trainees serve to review the learning success, determine knowledge gaps and to estimate skills (including reaction, concentration and creativity). Among others, the following criteria for evaluation are given in [50]:

- Correct response to mandatory specifications.
- Choice of optimal actions and their execution in compliance with the operational and emergency regulations.
- Safe use of control system equipment.
- Unambiguousness in the communication by use of correct expressions from the technical terminology.
- Compliance with existing time limits

The results of a trainee evaluation should be discussed individually with the respective trainees. An anonymous comparison encourages an improvement of personal skills. The cumulative group performance may be published.

4.5 Summary

The training necessity for control center staff and the benefits of such training for network operators have been presented in this chapter. Although it needs time and can be expensive and laborious, it has a number of advantages for both the control center staff and for network operators. Various methods exist for training the control center staff in the deregulated market. In this chapter, the following methods have been described and compared:

- Know-how transfer from experienced employees.
- Internal and external training events.
- Training of network restoration strategies.
- Business games.
- Use of training simulators (online, offline).

The method “Use of training simulators” compensates almost all the weaknesses of the other methods, has the same advantages as these other methods and has additionally further advantages. Despite the weaknesses of this method which can be compensated by applying the measures described, the strengths outweigh these weaknesses greatly. Therefore, and given the presented challenges and requirements in future distribution networks (in Chapter 2 and Chapter 3), this method is selected for training the control center staff.

The training evaluation is a very important process to control the achievement of the training. The results of an evaluation of the training process serve as feedback to improve, adapt, and optimize the training scenarios and the training system (including system operation, system performance, network component models, functionalities).
The results of an evaluation of the trainees serve to review the learning success, determine knowledge gaps, to estimate skills (including reaction, concentration and creativity). This evaluation process should be objective and iterative. To conduct it, clear and consistent criteria must be established and applied.
Chapter 5 Dynamic Power Training System

5.1 Introduction

As noted in the previous Chapter, the use of a network training simulator for training control center staff has many advantages compared to other methods. Therefore, this training method was selected for the training of control center staff. To implement a training platform for this training, an existing network training system at the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da) will be further developed and extended.

In Section 5.2, the existing network training system is presented and its structure is described. Then, the existing models and functions in that network training system are presented. Based on the mentioned challenges and requirements in future distribution networks (in Chapter 2 and Chapter 3), new models and functions are implemented on the one hand. On the other hand, some existing models and functions are extended and/or revised. The functions described in this section are called “functions for training”. These functions enhance the behaviour of the models and are relevant to the network simulation.

The “functions to support the training” are implemented in Section 5.3. These functions enable the design of the training and support the teaching and learning processes in a very efficient manner. In Section 5.4, the resulting new structure of the network training system (after the extensions and revisions) is presented.

5.2 Network training system at the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da)

5.2.1 Structure of the network training system

Computer-based monitoring and control systems, so-called SCADA systems (Supervisory Control And Data Acquisition) are used for monitoring and controlling industrial processes (e.g. electricity networks, water networks, heating networks).

A SCADA system consists of control computers (possibly replicated to provide redundancy) and workstations (possibly n units in parallel).
In a process, physical quantities are measured by instrumentation and sensors. The measured quantities are then packed in telegramms by computer-based devices, so-called PLCs (Programmable Logic Controllers) and transmitted. These telegramms (containing measured values, notifications, counter values and other information) are transmitted over remote control lines and received by the central control computer. Then, the control computer unpacks the telegramms and performs some processing on the data such as decryption, plausibility tests, comparisons, scaling, testing of limits. This is followed by the processing of the data for visualization on the workstation and by the data forwarding to the workstation. The process state is visualized on the workstation, the control center personal can judge the situation in the process and has the opportunity, if necessary, to intervene actively in the process.

When initiating a data transfer from the workstation to the process, the control computer first receives the data (e.g. commands, target values). It performs some processing on the data such as checking, scaling, encryption. The data is then packed in telegramms, sent over remote interfaces and remote control lines to the process. These are received, unpacked and processed by PLCs. Then the concerned actuators are controlled. Figure 5.1 shows an overview of the complete system.
An analogy to the described operation and the use of a SCADA system in technical processes, a network training system (NTS) for offline and risk-free training of the operation of electrical power networks was established in a collaboration between the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da) and the company repas AEG. It enables an authentic simulation in real time of electrical power networks and is used for the network operational training of control center staffs. The network training system (NTS) is composed of two computer systems connected together via Ethernet LAN (Local Area Network) and communicating together. One computer system represents the workstation and the other one is the network training simulator. **Figure 5.2** shows the system structure.

**Figure 5.1** Process monitoring and control with a SCADA system
5.2.1.1 Network training simulator

The network training simulator runs on a Linux platform. It consists of two software components:

- Control computer
- Network Simulator (NES)

The control computer is responsible for managing the communication process between the workstation and the network simulator (representing the process). When transmitting data in the monitoring direction (i.e. from the network simulator to the workstation) and in the command direction (i.e. from the workstation to the network simulator), all the described steps in Subsection 5.2.1 are performed.

The network simulator simulates the electrical network and performs a dynamic computation of the network behaviour. The responses (disturbances, changes), the behaviour of controllers, the dynamic intermediate states of the modelled network are computed in real time.

The network simulator consists of 3 subsystems that are each managed by organizing tasks. These tasks are, as illustrated in Figure 5.3:

- EMFORG for the subsystem 1
Each subsystem its turn consists of modules performing specific tasks.

The subsystem 1 comprises:

- the topology module (TOPMOD) for managing and computing the network topology.
- the parameter module (PARMOD) for computing the tap positions of transformers.
- the schedule module (FPLMOD) for the management of schedules of generators and loads.

The subsystem 2 includes:

- the load flow module (LFLMOD) for the load flow computation.
- the earth-fault module (ERDMOD) for the earth-fault current computation.
- the measurement module (MESSMOD) for the management and treatment of measurements.
- the short circuit module (KUSMOD) for the short circuit current computation.
The subsystem 3 includes:

- the protection module (SCHMOD) for the management of protection devices and the computation of reactions.
- the trigger module (TRGMOD) for the management of trigger actions.
- the control module (REGMOD) for the tap position control of transformers during the voltage control.
- the power plant control module (KWRMOD) for the power plant control.

The three organizing tasks (EMFORG, NETORG and AUSORG) have access to the static data model and each subsystem has its own dynamic data model. The static data model contains all invariant data of the network (e.g. global constants, data of all components in the network such as cable lengths, resistances) and the dynamic data model of each subsystem contains the computation results from the individual modules of the respective subsystem. Before a given subsystem starts its computations, the dynamic data model (contains computed dynamic data) from the preceding subsystem is first copied to the dynamic data model of the respective subsystem. Then computations are performed based on this data and other data. At the end of the computations, the updated dynamic data model is copied to the next subsystem. The copying takes place as soon as a release message from the receiving subsystem occurs; otherwise the transmitting subsystem waits for the release message.

All these data models are managed by the task INIT. This task performs an initialization of dynamic data during simulator launch and writes these data in the first dynamic data model (dynamic data model of EMFORG).

The Task “TIMMOD” triggers the network computation in a cycle of 1000 ms.

The Task “TRAINER” represents the trainer interface. All actions from the trainer (instructor) (e.g. setting of faults, setting of disturbances, performing changes in the network) are carried on over this interface.

The two other modules do not play any role in the context of network training and are therefore not discussed at this point.
5.2.1.2 Workstation

The workstation runs on a Windows platform and on it, the SCADA software RESY-PMC© is installed. RESY-PMC© is a proprietary software for monitoring and controlling processes. It is used worldwide in many companies, mainly for the operation of electricity, water, gas and heating networks. To create during the training an authentic environment as in a network control center, this software was installed on the workstation.

The data modelling of a simulated network and the maintenance of the data model are performed on the workstation. For this, the software RESY-PMC© offers a variety of programs:

- POE (Process Object Editor): This is the database with the templates and the process data.
- Dynadraw: The program for creating various types of displays (template displays, process displays).
- Nevis (Network Visualisation): The program for the visualization of the process on the workstation

5.2.2 Models and functions: Existing base

At the beginning of this thesis, many models were already integrated into the network training system. Any electrical network could be represented with these models and simulated. General network operational tasks and scenarios (busbar exchange, transformer exchange, short circuit search, earth-fault search, maintenance work with switching order) could be performed. A list of all existing models at the beginning of the thesis is given in Appendix 11.

To perform training of the control center staff taking into account the challenges mentioned in Chapter 2 due to the changes in the energy supply system and taking into consideration the applicable guidelines, laws and standards, an analysis of all existing models in the network training system (in terms of behaviour, functions, attributes and parameters for the operator and trainer) revealed that extension and revision of some
models are absolutely necessary. The respective models are highlighted in yellow in Appendix 12. In addition, new models and functions need to be implemented and integrated.

Within the framework of the extensions, two categories of functions will be distinguished in the network training system. There are “functions for training” and “functions to support the training”. The “functions for training” enhance the behaviour of the models and are relevant to the simulation of the network. The “functions to support the training” enable the design of the training and, support the teaching and learning processes in a very efficient manner.

A description of all models (new, revised and extended) and functions for training can be found in Section 5.2.3. In Section 5.3, the new functions to support the training are described.

5.2.3 Models and functions: new, extensions and revisions

Two subsections are considered here. The first subsection presents the new models and functions that have been implemented and integrated into the network training system. The second subsection shows the models already developed and, functions which have been extended and revised. The presented functions in this subsection refer only to “functions for training”.

For each model and each function, there is a brief description, together with the stated requirements, the modelling, the implementation, the demonstration, the visualization interface on the workstation and the trainer visualization interface. The requirements of the extended and revised models and functions before their respective extensions and revisions will be stated additionally.

The visualization interface on the workstation is needed for the visualization and the specification of process variables of equipment. For visualization purposes, process variable blocks must be set on the workstation for all new models. It is important in a first step to determine the process variables which must be exchanged between the network training simulator and the control system. For implementing this communication, some changes, extensions and modifications were carried out in the
network training simulator (including extension of structures and system files). On the workstation, process variable blocks were generated for all new models.

The trainer interface allows the trainer to perform changes on certain process variables of equipment and changes in the network, so as to simulate certain situations such as faults and disturbances. For this, trainer displays of all equipment and of some functions must be designed and implemented. Interface functions must be implemented on the network training simulator and visualization displays must be realized on the workstation to enable the communication between the trainer interface on the workstation and the network training simulator. The start and the operation of the trainer interface are carried out by the trainer (instructor) on the workstation.

Figure 5.4 and Figure 5.5 show respectively the overview display of the network and the overview display of the Smart Grid connected to the network.

Figure 5.4 Overview display of the network
5.2.3.1 New models and functions

For sake of clarity, the new models and functions are presented in summary here. Further details in terms of the requirements, modelling, implementation, demonstration, user interface on the workstation and trainer user interface of these items are presented in the supplementary volume accompanying this main volume.

5.2.3.1.1 Feed-in management

Since the integration of renewable energy plants in networks (transmission and distribution) progresses faster than the real network expansion in Germany, congestions often occur in networks. To bridge the time until the completion of the network...
expansion, the feed-in management serves as part of the measures to counteract possible network congestions. The feed-in management represents a temporary reduction of the power injection from renewable energy plants to avoid load flow problems in a network area until the expansion of the respective network area is completed [24, 25].

Within the scope of feed-in management nowadays, power reduction signals are sent to renewable energy plants (only wind turbines and photovoltaic systems). These plants react to the signal with a reduction of their power injection to the desired power level. Once the issue in the network is over, the plants receive a new signal for cancelling the power limitation. The power reduction percentage signals 100%, 60%, 30% and 0% of the agreed connection power are currently applied in Germany. The “agreed connection power” refers either to the rated power of the plant or to a specified power between network operator and plant operator/owner.

5.2.3.1.2 Frequency-dependent active power output

In the past, when the number of installed renewable energy plants was still low in Germany, these plants used to be disconnected simultaneously and automatically from the network as soon as the frequency value was above 50.2 Hz. This action was done to counteract the overfrequency situations. The overfrequency switch-off criteria were defined by the standard DIN VDE 0126 [52]. Renewable energy plants are gaining a significant systemic relevance as their installed power is currently very high and continuously increasing. A sudden and simultaneous disconnection of all these plants would cause a sudden large frequency deviation that could compromise the system security of the entire interconnected system causing stability problems, unwanted load and generator disconnections, network breakdown. The same applies in the case of a simultaneous connection of all renewable energy plants to the network as soon as the switch-on criteria are fulfilled.

For the mitigation of these risks, it was decided that renewable energy plants must contribute to the frequency support [17, 23, 53, 54].

Figure 5.6 shows the execution of the frequency support.
For a given renewable energy unit, as long as the frequency is between 47.5 Hz and 50.2 Hz, it feeds its generated active power into the grid. As long as the frequency is between 50.2 Hz and 51.5 Hz, the unit must decrease or increase (depending on the frequency increase or decrease) its active power injection with a gradient of 40% of $P_{50.2}$ per Hertz. $P_{50.2}$ represents hereby the frozen active power value at the instant when the grid frequency was 50.2 Hz. In case of continuous frequency variations within this frequency interval, there is a permanent active power injection increase and decrease on the ramp (see Figure 5.6). This increase and decrease is referred to as “characteristic curve ride” (in German “Fahren auf der Kennlinie”).

The unit must hold its active power injection constant at $P_{50.2}$:

- if the frequency falls below 50.2 Hz and
- as long as the frequency lies between 50.05 Hz and 50.2 Hz.

Once the frequency falls below 50.05 Hz and if at that moment the possible power output of the renewable energy unit is greater than its active power value $P_{50.2}$, then the active power output is allowed to increase with a maximum change rate of 10% of the agreed connection active power per minute.

If the frequency is below 47.5 Hz or above 51.5 Hz, an immediate automatic disconnection of the plant (containing the given unit) from the grid is engaged.

Figure 5.6 Active power reduction of renewable energy units in the case of overfrequency [6, 19]
In general, this control is performed automatically and does not require any external intervention from a control center.

5.2.3.1.3 Reactive power output of renewable energy plants

Although the active power output of some renewable energy plants is intermittent, the reactive power supply of these plants must be controlled so that static voltage stability is maintained. Thus, slow voltage changes (quasi-stationary) in the network can be kept within acceptable limits [20, 21, 53, 54]. At the same time, the dynamic grid support (realized through voltage control, reactive power compensation units, FACTS) should not be disturbed. During the planning of a plant connection to a network, the network operator specifies a method for reactive power supply at the respective network connection point based on particular network requirements [6, 19, 22, 23, 53, 54].

Currently, the following modes are available:

- Fixed reactive power: the reactive power supply depends on a set or specified reactive power value
- Fixed power factor: the reactive power to be provided is determined from the specified power factor and the instantaneous active power output of the plant. As long as \( \varphi \neq 0 \), the computation is based on the formula:
  \[ Q = P \cdot \tan(\cos^{-1} \varphi) \]  
  \text{Equation 5.1}

During the computation, the cases \( \cos \varphi \text{ (inductive)} \) and \( \cos \varphi \text{ (capacitive)} \) should be considered. If \( \varphi \neq 0 \), then \( Q = 0 \).

- Characteristic curve as a function of the active power: Depending on the instantaneous active power output of the plant, the determination of the reactive power supply is derived from a characteristic curve \( \cos \varphi(P) \). \text{Figure 5.7} shows an example of such a characteristic curve.
Figure 5.7 Example of a characteristic curve

- Reactive power voltage characteristic curve: Depending on the instantaneous voltage level at the grid connection point, the determination of the reactive power supply is derived from a characteristic curve Q(V).

The specification can be carried out through:
- a fixed value or if applicable, a schedule
- a characteristic curve as function of the operating point of the generating plant
- an online target value per remote control system (or other control techniques).

5.2.3.1.4 Frequency protection relay (realization of the overfrequency protection function)

The frequency protection relay is a relay used for protecting equipment against high and low frequencies. The working principle of the relay can be based on the frequency deviation, on the frequency change rate or on a combination of both [55].

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In this work, the focus is placed only on the first principle, because at the beginning of the work, the model of a frequency relay based on this principle was already implemented in the network training system. However, this model had only the underfrequency protection function (i.e. only protection against low frequencies was implemented). The model should now be extended with an overfrequency protection function.

When setting the frequency tripping value of an overfrequency protection level above the rated frequency value, the respective protection level works as overfrequency protection. Here, the set frequency tripping value should not be equal to the nominal frequency. As soon as the grid frequency deviates from the nominal frequency and violates the set frequency tripping value of a defined protection level, the relay is activated and the trigger timer is activated at the same time. The relay remains activated during the given delay time of the concerned protection level and if the violation is still present at the end of this delay time, the relay sends a trigger signal for actuating the switching element in the feeder at which the protected equipment is connected. The underfrequency protection function operates the same way.

Figure 5.8 shows the block diagram of the frequency protection relay.

![Block diagram of the frequency protection relay](image)

Figure 5.8 Block diagram of the frequency protection relay

5.2.3.1.5 Q-V-protection relay (reactive power - under voltage - protection)

In case of a voltage drop due to a system-critical fault (e.g. short circuit) in the network, some generation plants could absorb higher amount of reactive power from the grid. As a consequence of this plant behaviour, an amplification of the voltage drop in the network is to be expected. A Q-V-protection can be very useful to counteract this situation and to provide voltage support.

The following 5 criteria must be met [6, 22, 56, 57, 58, 59] for a tripping of a Q-V-protection relay:

Darlus France Mengapche
• All individual 3 phase voltages must be simultaneously lower than the set tripping voltage (3 criteria)
• The generation plant must absorb reactive power from the network and the absorbed reactive power must exceed the set threshold (4th criterion). According to [56], two working modes of the Q-V-protection are available for detecting the reactive power threshold.

1. Power factor threshold

![Diagram showing the four quadrants: Quadrant I (underexcited), Quadrant II (underexcited), Quadrant III (overexcited), Quadrant IV (overexcited). The diagram illustrates the working modes of the Q-V-protection.]

**Figure 5.9** Q-V-protection working mode “Power factor threshold”
2. Constant reactive power threshold

![Diagram showing Quadrants I to IV]

**Figure 5.10** Q-V-protection working mode “Constant reactive power threshold”

- In order to avoid an undesirable tripping (especially when a generation plant is idling), a power flow must be present to avoid an inadvertent operation of the reactive power detection. Therefore, an enabling current is set and the injected current of the plant must be greater than this enabling current (5th criterion).

If all 5 criteria are met simultaneously (AND-operation), the Q-V-protection relay is activated and both trigger timers (T1 and T2) are activated at the same time. The Q-V-protection remains activated during the given delay times and if the violation is still present at the end of these delay times, the Q-V-protection sends a trigger signal for actuating the switching elements. At the end of the delay time of the timer T1, a trigger signal is sent for the decoupling of the generation units in the plant. The end of the delay time of the second timer (T2) causes the disconnection of the entire plant at the grid connection point. Some special cases about the tripping times are described in [57].
It is also important to mention that a reference arrow system must be set for the operation of the protection. Additionally, the tripping quadrant(s) for the tripping of the protection should be selected for the specified reference arrow system.

The following values in Table 5.1 are recommended for a setting of Q-V-protection relays [56], where

Ir is the rated current of the plant,
Ur is the rated network voltage,
Sa is the agreed connection power of the plant. The “agreed connection power” refers either to the rated power of the plant or to a specified power between network operator and plant operator/owner.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting range</th>
<th>Recommended setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripping voltage</td>
<td>0.7 Ur to 0.9 Ur</td>
<td>0.85 Ur</td>
</tr>
<tr>
<td>Enabling current</td>
<td>0.02 Ir to 0.2 Ir</td>
<td>0.1 Ir</td>
</tr>
<tr>
<td>Tipping time at the generation unit</td>
<td>0.1 s to 2 s</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Tripping time at the network connection point</td>
<td>0.1 s to 2 s</td>
<td>1.5 s</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0° to 6°</td>
<td>Max. 3°</td>
</tr>
<tr>
<td>Reactive power threshold</td>
<td>0 to 0.05 Sa, underexcited</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.11 shows the block diagram of the Q-V-protection relay.
5.2.3.1.6 Underimpedance protection relay

A short circuit in the network leads to voltage drops and to the injection of high short circuit currents from the grid main connections and from rotating generators (for synchronous generators, the short circuit current would be about 8 times the rated current; for induction generators, the fault current would be approximately 6 times the rated current [22]).

[Note: These are approximate values. For an accurate calculation, network impedances must be taken into account.]

Based on the expected level of the short-circuit contribution of a generator, the parameter setting of protective devices for protection against short-circuit currents is conducted. However, generators with converters such as photovoltaic systems or wind turbines have their maximum short-circuit currents at about 1.0 Ir to 1.5 Ir (Ir is the rated current). Given the amount of this short-circuit current, the use of a conventional protection devices (e.g. definite time-delay overcurrent protection relays) leads to false interpretations and inadvertent disconnections. To avoid this situation, the underimpedance protection relay is used. This relay evaluates, in addition to the injected current, the voltage at the connection point of the generation plant. As soon as a voltage drop is detected at the connection (voltage falls below the set tripping voltage) and the
injected current exceeds the set tripping current, the relay is activated and the trigger timer is activated at the same time. The relay remains activated during the given delay time and if the violation is still present at the end of this delay time, the relay sends a trigger signal for actuating the switching element in the feeder at which the protected equipment is connected.

**Figure 5.12** shows the block diagram of the underimpedance protection relay.

![Block diagram of the underimpedance protection relay](image)

**Figure 5.12** Block diagram of the underimpedance protection relay

### 5.2.3.1.7 Hydroelectric power plant (storage and run-of-the-river)

A hydroelectric power plant generates electricity by first converting kinetic energy from the water motion into mechanical energy and then the mechanical energy into electrical energy. Mechanical energy is produced by the transfer of kinetic energy from flowing water on a turbine. The turbine is set in motion and drives directly via a shaft or via an intermediate gear a generator that converts the mechanical energy into electrical energy [60].

Various types of hydroelectric power plants (run-of-the-river, storage, pumped-storage, cavern, wave, tidal power plants) [60] can be distinguished. In this thesis, the focus is placed only on hydroelectric run-of-the-river, storage or pumped-storage power plants. For energy production, water is stored differently in these different power plant types. A run-of-the-river power plant is not able to store water (thus energy). The instantly flowing water is immediately used for electrical energy production.
However a hydroelectric storage power plant has a storage in form of an artificial or natural water reservoir and can control the water volume. A special form of storage hydroelectric power plant is the hydroelectric pumped storage power plant. It has two reservoirs (upper reservoir and lower reservoir). For electrical energy generation (generation mode) the water flows from the upper reservoir into the lower reservoir and drives the turbine-shaft-generator set. For electrical energy storage (pumping mode), water is transferred from the lower reservoir to the upper reservoir using pumps. For this purpose, the generator operates as a motor and drives the pumps.

Models of a run-of-the-river power plant and of a storage power plant are required in the network training system. A hydroelectric pumped storage power plant model was already present in the network training system and needs only to be extended.

5.2.3.1.8 Virtual power plant

As already mentioned and described in Subsection 3.2.1, two types of virtual power plants are to be distinguished. These are virtual power plant type 1 (VPP 1) and virtual power plant type 2 (VPP 2).

A virtual power plant type 2 should be implemented into the network training system.

5.2.3.1.9 Transformer taps intertripping circuit

The transformer taps intertripping circuit is a mechanism for parallel tap position changing of 2 transformers connected in parallel. The tap position difference between two transformers connected in parallel is continuously kept constant and is limited to a predefined maximum tap position difference. Thus, a limitation and prevention of possible high circulating currents, which would lead to an overloading of the transformers and to a disconnection of these by protection devices, can be achieved.

Consider two transformers connected in parallel. Each transformer has a settable transformer taps intertripping circuit state (“MASTER” or “SLAVE”). The states are mapped on a suitable computer-based system and the necessary actions are implemented on it.
If the state of one of both transformers is “MASTER”, then a tap position change at the respective transformer will cause the sending of a pulse for changing the tap position of the other transformer. However a received pulse due to a tap position change at the other transformer will be ignored by the respective transformer.

If the state of one of both transformers is “SLAVE”, then a tap position change at the respective transformer is performed upon reception of a pulse from the other transformer. However a tap position change at the respective transformer cannot lead to the sending of a pulse to the other transformer.

If both transformers are not connected in parallel, then there is no reaction from the transformer taps intertripping circuit in case of tap position changes.

Table 5.2 shows the possible states of the voltage controller and the transformer taps intertripping circuit at two transformers connected in parallel. From these states, the reactions at one of both transformers (in this case, transformer 2) are derived in case of tap position changes at the other transformer (in this case, transformer 1).

### Table 5.2 Transformer taps intertripping circuit at two transformers connected in parallel

<table>
<thead>
<tr>
<th>Transformer 1 Voltage controller</th>
<th>Transformer 1 Tap intertripping</th>
<th>Transformer 2 Voltage controller</th>
<th>Transformer 2 Tap intertripping</th>
<th>Reaction at transformer 2 in case of a tap position change at transformer 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>SLAVE</td>
<td>OFF</td>
<td>SLAVE</td>
<td>No reaction</td>
</tr>
<tr>
<td>OFF</td>
<td>MASTER</td>
<td>OFF</td>
<td>SLAVE</td>
<td>Tap position change</td>
</tr>
<tr>
<td>ON</td>
<td>SLAVE</td>
<td>ON</td>
<td>SLAVE</td>
<td>No reaction</td>
</tr>
<tr>
<td>ON</td>
<td>MASTER</td>
<td>ON</td>
<td>MASTER</td>
<td>Tap position change</td>
</tr>
<tr>
<td>OFF</td>
<td>SLAVE</td>
<td>OFF</td>
<td>MASTER</td>
<td>No reaction</td>
</tr>
<tr>
<td>OFF</td>
<td>MASTER</td>
<td>OFF</td>
<td>MASTER</td>
<td>No reaction</td>
</tr>
<tr>
<td>ON</td>
<td>SLAVE</td>
<td>ON</td>
<td>SLAVE</td>
<td>No reaction</td>
</tr>
<tr>
<td>ON</td>
<td>MASTER</td>
<td>ON</td>
<td>SLAVE</td>
<td>No reaction</td>
</tr>
<tr>
<td>OFF</td>
<td>SLAVE</td>
<td>ON</td>
<td>SLAVE</td>
<td>No reaction</td>
</tr>
<tr>
<td>OFF</td>
<td>MASTER</td>
<td>ON</td>
<td>SLAVE</td>
<td>Tap position change</td>
</tr>
<tr>
<td>ON</td>
<td>SLAVE</td>
<td>ON</td>
<td>SLAVE</td>
<td>No reaction</td>
</tr>
<tr>
<td>ON</td>
<td>MASTER</td>
<td>ON</td>
<td>MASTER</td>
<td>Tap position change</td>
</tr>
<tr>
<td>OFF</td>
<td>SLAVE</td>
<td>ON</td>
<td>MASTER</td>
<td>No reaction</td>
</tr>
<tr>
<td>OFF</td>
<td>MASTER</td>
<td>No reaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>--------</td>
<td>-------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ON</td>
<td>SLAVE</td>
<td>No reaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ON</td>
<td>MASTER</td>
<td>No reaction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It may happen that the tap position difference increases by activated transformer taps intertripping circuit, e.g. when the tap position of a transformer (in “SLAVE” mode) is been changed. In order to limit the tap position difference in such a case, a maximum tap position difference between both transformers is set. Once this is reached, no additional tap changes that would lead to a violation of the tap position difference limit are executed.

Both red-marked cases are special. Since the voltage controller of transformer 2 is active, that controller reacts as soon as the voltage at the secondary side gets out of the specified voltage range. Thus, the maximum tap position difference could be achieved. Once this is reached, additional tap changes initiated by the voltage controller, which may lead to a violation of the tap position difference limit, cannot be executed.

### 5.2.3.1.10 Transformer switch position intertripping circuit

The transformer switch position intertripping circuit is a mechanism for automatically switching off both sides of a transformer immediedly after a switching element on the primary or secondary side is actuated by an installed protection relay (e.g. definite time-delay overcurrent protection relay, distance relay) due to a fault in the network. As a result, the transformer is on both sides completely disconnected from the network, thus avoiding for example potentially dangerous high open-circuit voltages. Figure 5.13 illustrates the effect.
Assume that a short-circuit occurs at the busbar on the secondary side of the transformer (Figure 5.13a). If as a result of the fault the switching element on the secondary side of the transformer is actuated by a protection relay (Figure 5.13b), then the switching element on the primary side of the transformer is automatically actuated by the transformer switch position intertripping circuit (Figure 5.13c). At the end, the transformer is switched off on both sides (Figure 5.13d).

The same procedure applies in the case of an actuation of the switching element on the primary side of the transformer by a protection relay due to a fault.

A manual switching on site or a remote switching per command of one of both switching elements does not cause any reaction of the transformer switch position intertripping circuit.

5.2.3.1.11 Transmission interface frequency adjustment

The frequency influencing is a function to actively influence the frequency in the highest upstream level of a modelled interconnected network. This function enables the simulation of frequency problems throughout the modelled network with effects on all network levels. For example, a frequency problem can be simulated in an interconnected system by using the function. As a consequence, reactions from frequency controllers, frequency-dependent active power controllers of renewable energy plants and protection relays in the entire network can be expected.

Figure 5.13 Operation of the transformer switch position intertripping circuit
5.2.3.1.12 Transmission interface voltage adjustment

The voltage influencing is a function to actively influence the voltage on the highest upstream level of a modelled interconnected network. This function enables the simulation of voltage problems in the highest upstream network level with effects on all downstream network levels. For example, voltage problems can be simulated in the transmission grid by using the function. As a consequence, reactions from voltage controllers, reactive power controllers of plants and protection relays at all network levels can be expected.

5.2.3.2 Extended and revised models and functions

For sake of clarity, the extended and revised models and functions are presented in summary here. Further details in terms of the requirements, modelling, implementation, demonstration, user interface on the workstation and trainer user interface of these items are presented in the supplementary volume accompanying this main volume.

5.2.3.2.1 Wind turbine

A wind turbine generates electricity by first converting kinetic energy from the movement of the wind into mechanical energy and then the mechanical energy into electrical energy. Mechanical energy is produced by the transfer of kinetic energy from the movement of wind on a turbine. The turbine is set in motion and drives directly via a shaft or via an intermediate gear a generator that converts the mechanical energy into electrical energy. The generated electrical energy is fed by the generator directly or via an intermediate inverter to the grid. If the voltage at the output of the plant and the grid voltage do not match, a transformer is connected between the plant and the power grid.

5.2.3.2.2 Photovoltaic plant

A photovoltaic system (PV system) consists of a solar generator and an inverter. The solar generator is an energy converter consisting of many interconnected solar modules.
The principle of operation of a solar module is based on the photoelectric effect in which electrical energy is obtained from sunlight. If light hits the surface of a solar module with a certain amount of irradiance, a voltage appears at the terminals of the module. If a load is connected at the terminals, then a current flows and the power generated depends on the solar irradiance.

A solar module consists of many interconnected solar cells. The solar modules are connected together in series to form strings and the strings are in turn connected in parallel. This results in the solar generator. Since the PV system generates a DC voltage, an inverter is used for the connection to the AC grid. If the AC voltage at the output of the inverter and the grid voltage do not match, a transformer is connected between the inverter and the power grid.

5.2.3.2.3 Biogas power plant

A biogas power plant consists of a gas storage, a gas engine and a generator. A biogas power plant generates electricity by first converting the energy stored in the biogas (as fuel) into mechanical energy and then the mechanical energy into electrical energy. This mechanical energy is produced by the combustion of biogas in the gas engine. The gas motor drives via the coupled shaft the generator, which then converts mechanical energy into electrical energy. Biogas is a combustible gas and is obtained by fermentation of biomass of different kinds. The resulting biogas is stored in a gas storage. Depending on the methane content of the biogas, the heating value of the biogas varies between 4 and 7.5 kWh/m³ [61].

5.2.3.2.4 Voltage protection relay

The voltage protection relay is a relay used for the protection of equipment against dangerous overvoltages and undervoltages. The relay has an overvoltage and undervoltage protection function (for detecting overvoltages and undervoltages respectively), and works on the principle of voltage deviation. When configuring the overvoltage protection function, the protection levels are staggered and a voltage tripping value is entered for each level depending on the number of desired protection levels. Each tripping value must always be above the

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nominal voltage. When setting the undervoltage protection function, the voltage tripping values must however be below the nominal voltage. In both cases, the values must not be equal to the network nominal voltage.

As soon as the network voltage deviates from the network nominal voltage and violates the set tripping value of at least one of the defined voltage protection level, the relay is activated and the trigger timer of the highest concerned protection level is activated at the same time. The relay remains activated during the given delay time of the highest concerned protection level and if the violation is still present at the lapse of this delay time, the relay sends a trigger signal for actuating the switching element in the feeder at which the protected equipment is connected. Figure 5.14 shows the block diagram of the voltage protection relay.

Figure 5.14 Block diagram of the voltage protection relay

5.3 New functions to support the training

For sake of clarity, a summary of the new functions to support the training is presented here and further details of the approach and the implementation in the network training system are presented in the supplementary volume accompanying this main volume.
5.3.1 Snapshot

The function “Snapshot” is used to create snapshots of the system state at any time. For the preparation of the training, this function enables the creation of snapshots, which will serve as network initial states of training tasks. Thus any necessary switchings and adjustments which would have been conducted prior to the accomplishment of training tasks to achieve a suitable network state are omitted. During the training, the function allows for the convenient and rapid generation of specific network cases or snapshots of the system state. These snapshots could be used later after training and represent material for review and discussion between the trainer and the trainee. The generated snapshots are given a name and a brief description, and are then stored on the network simulator. These can later be loaded at any time.

5.3.2 Scenario

This function allows the trainer to load one of several stored scenarios in the simulator and to use it to initiate a training session. A scenario is built on the basis of the original network state (i.e. predefined network state loaded at every start of the simulator), the topology from the static data model and generated schedules for loads and generators. By using the generated scenarios, training sessions with the same topology at various supply and consumption situations are possible.

5.3.3 Training session

This function is used for the recording and the playback at a later time of an entire training session. When using this function during the training, all events (e.g. switching operations, tap position change) initiated by the trainer and by the trainee are stored together with corresponding time information (from the simulation clock time) in an event list on the network training simulator. At the end of the recording, the event list can be accessed at any time. A specific time of the recording in the list can be selected to restore the entire...
system state to that selected moment and to play back the training session (recording) starting from that time. After the training session, the recording can be used as material for meetings and discussions between the trainer and the trainee about decisions taken, actions performed and the consequences.

### 5.3.4 Simulation management

This function enables the trainer to halt the simulation during a training session. This allows pauses and interruptions (for discussion, agreement and consultation). Thereafter, the simulation is continued from the breakpoint. The function also enables the setting of the simulation time by the trainer. Suppose the operator starts the network training system at 9:00 (computer time) and would however like to perform a simulation with schedule values starting from 12:00. Instead of waiting 3 hours, a time jump can be performed by using this function. This saves time and offers greater flexibility. A time jump back into the past is also possible.

The functions “Snapshot”, “Scenario” and “Training session” make use of this function automatically to halt the training simulator before performing their respective operations and to continue the simulation thereafter.

### 5.4 Network training system at the h_da: New Structure

The implementation of the mentioned extensions in the network training system led to changes in the structure of the network simulator. Already existing modules were extended and adapted. The network simulator was extended with a new module (marked in green in Figure 5.15). This new module is responsible for the management of training sessions, scenarios, snapshots and the simulation management. Figure 5.15 shows the new structure of the network simulator.
Figure 5.15 New structure of the network simulator

A list of all:
- new models and functions,
- extended and revised models and functions already existing

is given in Appendix 12.

In addition, new building block templates were created for the visualization of the new models on the workstation. The building block templates of existing models were extended and revised.

5.5 Summary

In this chapter, the existing network training system at the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da) was used for the development of an extended training platform for the training of the operation management of Smart Grids. It enables an authentic simulation in real time of electrical power networks and is used for the network operational training of control center staff. It enables an offline and risk-free training of the operation of electrical power networks. That network training system (NTS) consists of two computer systems connected to each other via Ethernet LAN.
(Local Area Network) and communicating together. One computer system represents the workstation and the other one is the network training simulator. During the development of the training platform, new models and functions were created on the one hand. On the other hand, some existing models and functions were extended and/or revised. These functions are called “functions for training”. The implementation of these models and functions was conducted under consideration of existing guidelines and laws. Moreover, “functions to support the training” were implemented. These are used to design the training, to support the teaching and learning processes in a very efficient manner.

Existing modules in the network training system were extended and adapted during the development. A new module was also integrated. Additionally, new building block templates were developed for the visualization of the new models on the workstation. The building block templates of existing models were extended and revised.
Chapter 6  Tools for the Operational Management of Smart Grids

6.1  Introduction

As mentioned in Chapter 3, the transformation of current distribution networks into Smart Grids leads to the emergence of new complex tasks in network operational management. Control center staff can be prepared for that transformation through training (Chapter 4). Despite the training, control center staff needs additional support to efficiently, quickly and optimally manage the Smart Grid and solve all problems occurring in it. This support can be provided by algorithms (as tools). Some of these algorithms should be run on Grid Managers (Chapter 3) and should enable the Grid Managers to autonomously solve local problems. Others should run on the SCADA system in the control center and should support the control center staff by performing computations, generating operational recommendations and delivering indications. In this chapter, various tools are presented in detail.

In Section 6.2, a method for power loss reduction, improvement of voltage profile and reduction of reactive power flow in networks through adjustment of the reactive power supplies is described and demonstrated. For efficient congestion and power flow management, a new approach based on causer pays generation and load adjustments is presented and demonstrated in Section 6.3. In Section 6.4, a new voltage management approach consisting in topology-based generation and load adjustments is presented and demonstrated. A new approach for state estimation in distribution network with a few measurements is described and demonstrated in Section 6.5. In the last section, further important tools for the management of Smart Grids are briefly described.

6.2  Improved Relative Electrical Distance (RED) method for power loss reduction, improvement of voltage profile and reduction of reactive power flow in networks by controlling the reactive power supply

Some network components (e.g. transformer) and connected consumers (e.g. motors) need inductive reactive power for operating. This reactive power is generated by the grid and by some components such as generators and reactive power compensation units. Nevertheless, problems (e.g. congestions and voltage limit violations) and
negative side effects (e.g. reduction of the network transmission capacity, increase of network losses, high voltage drops) could occur during power delivery. These problems restrict the network operation and result in costs to the network operator. A new technically and economically efficient approach is presented, implemented and demonstrated in the following subsections.

6.2.1 Description of the new approach

This approach allows an efficient reactive power flow in a network by adjustment of the reactive power supplies. For that, the RED concept (Relative Electrical Distance) is used and enables the determination of the reactive power supply of a generator to cover a load demand as a function of the topological distance of both components from one another. That means, the closer a generator and a load are to each other, the greater the reactive power supply from the generator to meet the load demand. Through the use of this concept, a reduction of the reactive power transmission throughout the network is achieved. This reduction leads to an improvement of the voltage profile and an increase of the available transmission capacity on the lines. This adjustment can sometimes solve congestion, overloads and voltage limit violations.

In real network operation, the mentioned adjustments can be performed periodically (due to load changes during the day) so as not to be carried out only after the occurrence of problems (e.g. power flow problems, voltage problems).

The RED concept is explained by considering a system with in total n buses (\( g \) generator buses and \( n - g \) load buses). For the system considered, the following equation can be written

\[
\begin{bmatrix}
I_G \\
I_L
\end{bmatrix} =
\begin{bmatrix}
Y_{GG} & Y_{GL} \\
Y_{LG} & Y_{LL}
\end{bmatrix}
\begin{bmatrix}
V_G \\
V_L
\end{bmatrix}
\]

\text{Equation 6.1}

where

\( I_G, I_L \) are complex current vectors at generator nodes and load nodes respectively,

\( V_G, V_L \) are complex voltage vectors at the generator nodes and load nodes respectively.

\( Y_{GG}, Y_{GL}, Y_{LL} \) and \( Y_{LG} \) are part of the network admittance matrix (Y-bus matrix).

Rearranging \text{Equation 6.1}, the following equation is obtained.
\[
\begin{bmatrix}
V_L \\
I_G
\end{bmatrix} =
\begin{bmatrix}
Z_{LL} & F_{LG} \\
K_{GL} & Y_{GG}
\end{bmatrix}
\begin{bmatrix}
I_L \\
V_G
\end{bmatrix}
\]  

Equation 6.2

In Equation 6.2,

\[ F_{LG} = -Y_{LL}^{-1}Y_{LG} \]  

Equation 6.3

\[ K_{GL} = Y_{GL}Y_{LL}^{-1} \]  

Equation 6.4

\[ Y_{GG} = Y_{GG} - Y_{GL}Y_{LL}^{-1}Y_{LG} \]  

Equation 6.5

The elements of the matrix \( F_{LG} \) are complex, and its columns correspond to the generator bus numbers and its rows correspond to the load bus numbers. This matrix gives the relation between the load bus voltages and generator bus voltages. From it, the information about the relative electrical location of load nodes from generator nodes can be derived. It is known as the relative electrical distance (RED) and is computed as:

\[ RED = M - \text{abs } F_{LG} \]  

Equation 6.6

where \( M \) is the unity matrix of size \( n_g \times n_g \).

It is desired that a generator’s share to a nearby load is more than its share to a far-off load, as this would generally result in minimizing the system losses, improving voltage magnitudes and improving the voltage profile.

Based on the \( F_{LG} \) matrix, the desired generation proportions matrix \( D_{LG} \) can also be obtained as

\[ D_{LG} = \text{abs } F_{LG} \]  

Equation 6.7

Each element of this matrix represents the desired generation proportion of each generator to each load. For given load patterns, if the power from each generator is scheduled as per the \( D_{LG} \) matrix, the system will observe minimum transmission losses, improved voltage magnitudes and better voltage profile.

From the \( D_{LG} \) matrix and for given load patterns, the desired generation schedules (DGS) can be obtained as:

\[ DGS_i = \sum_{j=i+1}^n D_{ji} \times Q_j \]  

Equation 6.8

where
$Q_j$ is the given reactive power schedule of the load at the $j^{th}$ load bus,

$D_g$ is the generation proportion taken from the $D_{LG}$ matrix,

$DGS_i$ is the desired generation schedule of the generator at the $i^{th}$ generator bus.

As example, let us consider the case6ww in MATPOWER (the line data are given in Appendix 9). Figure 6.1 shows the network structure.

Figure 6.1 Case6ww network

The $F_{LG}$ matrix for this network is given by:

$$F_{LG} = \begin{bmatrix}
0.3404 - 0.0477i & 0.6136 + 0.0411i & 0.0517 + 0.0045i \\
0.2735 - 0.0231i & 0.3691 + 0.0112i & 0.3684 + 0.0080i \\
0.0494 - 0.0010i & 0.3336 + 0.0274i & 0.6226 - 0.0279i
\end{bmatrix}$$
The elements of the $F_{LG}$ matrix are complex, its columns corresponds to the generator bus numbers 1, 2, 3 and rows corresponds to the load bus numbers 4, 5, 6. It can be observed that the sums of the row elements of the $F_{LG}$ matrix are close to (1.0, 0.0).

Using Equation 6.7, the $D_{LG}$ matrix gives

$$D_{LG} = \begin{bmatrix} 0.3437 & 0.6150 & 0.0519 \\ 0.2745 & 0.3693 & 0.3684 \\ 0.0494 & 0.3348 & 0.6232 \end{bmatrix}.$$  

If the load at bus 4 is 100 MVAr, then generator 1 should deliver $0.3437 \times 100$ MVAr = 34.37 MVAr, generator 2 should give $0.6150 \times 100$ MVAr = 61.50 MVAr and generator 3 should deliver $0.0519 \times 100$ MVAr = 5.19 MVAr. This procedure is also applied to load 5 and load 6.

In many research papers dealing with and using the RED concept [62, 63, 64, 65, 66, 67, 68], the networks considered always have only one element (either a generator or a load) connected at each node. The case where a generator and a load are connected simultaneously at a same node is not yet been treated, although this is becoming very common in distribution networks with the integration a distributed renewable energy generation plants.

To deal with this special case, the RED concept has been expanded in this thesis. The main idea is to transform the concerned nodes into either generator or load nodes, so that the RED concept as already described could still be applied.

To explain the new idea, let us consider the simple 6 bus radial network in Figure 6.2.

![Figure 6.2](image)

Figure 6.2 A simple 6 bus system
There is a generator and a node connected simultaneously at node 5. The goal now is to transform node 5 into either a generation or a load node. For this, the following three situations are possible:

Situation 1: if the generator can cover the actual load demand (i.e. $Q_{G5_{-\text{max}}} > Q_{L5}$), the reactive power of the generator is set equal to the reactive power of the load ($Q_{G5} = Q_{L5}$) and then node 5 is treated as a generator node with a “virtual generator” able to still deliver only ($Q_{G5_{-\text{max}}} - Q_{L5}$) reactive power. This leads to a $D_{LG}$ matrix consisting of 4 columns (for G1, G2, G5 and G6) and 2 two rows (for L3 and L4).

Situation 2: if the generator cannot cover the actual load demand (i.e. $Q_{G5_{-\text{max}}} < Q_{L5}$), the reactive power of the generator is set equal to his limit ($Q_{G5} = Q_{G5_{-\text{max}}}$) and then node 5 is treated as a load node with a “virtual load” having a reactive demand of ($Q_{L5} - Q_{G5_{-\text{max}}}$). This leads to a $D_{LG}$ matrix consisting of 3 columns (for G1, G2 and G6) and 3 rows (for L3, L4 and L5).

Situation 3: if the generator can exactly cover the actual load demand (i.e. $Q_{G5_{-\text{max}}} = Q_{L5}$), the reactive power of the generator is set equal to the reactive power of the load ($Q_{G5} = Q_{L5}$) and then node 5 is treated as a generator node with a “virtual generator” which has reached his limit (no extra reactive power can be delivered). This leads to a $D_{LG}$ matrix consisting of 4 columns (for G1, G2, G5 and G6) and 2 rows (for L3 and L4).

Here,

$Q_{G5_{-\text{max}}}$ is the reactive power limit of the generation at node 5,

$Q_{G5}$ is the reactive power generation of the generator at node 5,

$Q_{L5}$ is the reactive power demand of the load at node 5.

Once the $D_{LG}$ matrix is obtained, the desired generation schedules can be computed from Equation 6.8.
There is another problem which can occur while using the RED concept as described and used in many research papers. This has not been observed closely and treated till now. It may happen for a given generator that the desired generation as given by the DGS matrix is greater than the generation limits. To deal with this situation, the RED concept has been expanded in this thesis. To explain the new idea, consider the Case6ww (Figure 6.1) again.

The $F_{LG}$ and $D_{LG}$ matrices for this network are given by

$$F_{LG} = \begin{bmatrix}
0.3404 - 0.0477i & 0.6136 + 0.0411i & 0.0517 + 0.0045i \\
0.2735 - 0.0231i & 0.3691 + 0.0112i & 0.3684 + 0.0080i \\
0.0494 - 0.0010i & 0.3336 + 0.0274i & 0.6226 - 0.0279i
\end{bmatrix}$$

$$D_{LG} = \begin{bmatrix}
0.3437 & 0.6150 & 0.0519 \\
0.2745 & 0.3693 & 0.3684 \\
0.0494 & 0.3347 & 0.6232
\end{bmatrix}$$

The following DGS matrix can be derived

$$DGS = \begin{bmatrix}
17.185 & 30.75 & 2.595 \\
27.45 & 36.93 & 36.84 \\
7.41 & 50.21 & 93.48
\end{bmatrix}$$

Given the load reactive power demands $Q_{L4} = 50$ MVAR, $Q_{L5} = 100$ MVAR, $Q_{L6} = 150$ MVAR, it can be derived from the DGS matrix that the generator should produce (columnwise summation)

$Q_{G1.desired} = 52.045$ MVAR, $Q_{G2.desired} = 117.89$ MVAR, $Q_{G3.desired} = 132.915$ MVAR.

Let us assume the maximum reactive power limits of the generators are set to

$Q_{G1.max} = 300$ MVAR, $Q_{G2.max} = 150$ MVAR, $Q_{G3.max} = 100$ MVAR.

It can be seen that $Q_{G3.desired} > Q_{G3.max}$.

The following procedure is applied to solve this situation:

1) Find the generator with the most highest missing power value $(Q_{G.desired} - Q_{G.max})$
In this example it is generator 3

2) Set the reactive power generation of that generator to its limit

\[ Q_{G3} = Q_{G3\_max} \]

3) Compute the factor corresponding to the ratio of missing power to desired power for the selected generator

\[ \text{Factor} = \frac{(Q_{G\_\text{desired}} - Q_{G\_\text{max}})}{Q_{G\_\text{desired}}} \]  

\text{Equation 6.9}

For the example, \[ \text{Factor} = \frac{(Q_{G3\_\text{desired}} - Q_{G3\_\text{max}})}{Q_{G3\_\text{desired}}} = 0.2476 \]

It means around 24.76% of the desired power from generator 3 are still needed.

4) Perform a multiplication of the factor by all load demands to get the amount of power which could not be delivered by the given generator to the loads due to the missing power.

\[ [Q_{L\_\text{lacking}}] = \text{Factor} \times [Q_L] \]  

\text{Equation 6.10}

For the example, \[ Q_{L\_\text{lacking}} = \text{Factor} \times [Q_{L4} , Q_{L5} , Q_{L6}] = 0.2476 \times [50 , 100 , 150] = [12.38 , 24.76 , 37.14] \]

This missing power should now be delivered by other generators present in the network.

Before doing this, the column with the selected generator is removed from the DLG and DGS matrices to get the new modified DLG and DGS matrices.

\[ D_{LG\_\text{changed}} = \begin{bmatrix} 0.3437 & 0.6150 & 0.0519 \\ 0.2745 & 0.3693 & 0.3684 \\ 0.0494 & 0.3347 & 0.6232 \end{bmatrix}, \quad D_{G\_\text{changed}} = \begin{bmatrix} 17.185 & 30.75 & 2.595 \\ 27.45 & 36.93 & 36.84 \\ 7.41 & 50.21 & 93.48 \end{bmatrix} \]

5) Perform a multiplication of the computed missing power of each load by the corresponding desired generation proportions in the \[ D_{LG\_\text{changed}} \] matrix to get the needed generation schedules (NDS) from other generators in the network for supplying the missing power.

\[ NGS_{ji} = D_{ji} \times Q_{\text{lacking}_j} \]  

\text{Equation 6.11}
where

\( Q_{\text{tackling}_j} \) is the determined missing reactive power schedule for the load at the \( j^{th} \) load bus,

\( D_{ji} \) is the generation proportion taken from the \( D_{LG,\text{changed}} \) matrix,

\( NGS_{ji} \) is the needed generation schedule from the generator at the \( i^{th} \) generator bus to supply the missing power of the load at the \( j^{th} \) load bus.

For this example,

\[
NGS = \begin{bmatrix} 4.2550 & 7.6137 \\ 6.7966 & 9.1439 \\ 1.8347 & 12.4307 \end{bmatrix}
\]

6) \textit{Update the} \( DGS_{\text{changed}} \) \textit{matrix by adding the} \( NGS \) \textit{matrix to it}

\[
DGS_{\text{changed, new}} = DGS_{\text{changed, old}} + NGS
\]

\textit{Equation 6.12}

For the example,

\[
DGS_{\text{changed}} = \begin{bmatrix} 17.185 & 30.75 \\ 27.45 & 36.93 \\ 7.41 & 50.21 \end{bmatrix} + \begin{bmatrix} 4.2550 & 7.6137 \\ 6.7966 & 9.1439 \\ 1.8347 & 12.4307 \end{bmatrix} = \begin{bmatrix} 21.44 & 38.3637 \\ 34.2466 & 46.0739 \\ 9.2447 & 62.6407 \end{bmatrix}
\]

7) \textit{Compute the new desired generation schedules from all generators}

It can now be derived from the \( DGS_{\text{changed}} \) matrix that the generators should produce (columnwise summation)

\( Q_{G1,\text{desired}} = 64.9313 \text{MVar} \), \( Q_{G2,\text{desired}} = 147.0783 \text{MVar} \).

\( Q_{G3,\text{desired}} \) has been set to \( Q_{G3,\text{desired}} = 132.915 \text{MVar} \).

Now for each generator, the desired generation as given by the DGS matrix is greater than the generation limit.

This procedure is performed until all desired generation output levels for each generator as given by the DGS matrix are within the respective generation limits. Both the maximum and minimum limits have to be considered.
It is also important to mention that the approach requires that one generator in the network is set as a slack generator. While performing the procedure, if there is missing power which cannot be supplied by the generators (apart of the slack) in the network, it is supplied by the slack generator. For example, if a low voltage network is considered, the transformer connecting it to the medium voltage network is considered as the slack injection and the missing power would come from the medium voltage network.

In total, the two extensions shown (procedure for the modification of nodes and procedure for the adaptation of desired powers) are integrated in the conventional RED concept. The new RED concept could be used to get the desired reactive power supply from generators for a given network topology and a given load demand. The benefits have already been mentioned.

6.2.2 RED based tool for reactive power supply management

To demonstrate the capability of the approach, a tool was developed using Matlab [69]. This consists of the software package MATPOWER [70] for load flow calculation, the Matlab program developed for the RED concept and interfaces (user interface, file interfaces) for inputs and outputs.

6.2.3 Scenarios and results

6.2.3.1 Scenario with the case8 network and results

Suppose the case8 network illustrated in Figure 6.3. The network has:

- a radial structure,
- 8 nodes,
- 3 generators (connected at the nodes 1, 4 and 8),
- 7 loads (connected at the nodes 2, 3, 4, 5, 6, 7 and 8),
- 7 branches and
- no shunt.

The network data are given in Appendix 14.
The results in Figure 6.4 and Figure 6.5 are obtained after running a load flow calculation on the network before applying the RED method.

**Figure 6.3** Case 8 network

<table>
<thead>
<tr>
<th>System Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>How many?</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Buses</td>
</tr>
<tr>
<td>Generators</td>
</tr>
<tr>
<td>Committed Gen</td>
</tr>
<tr>
<td>Loads</td>
</tr>
<tr>
<td>Fixed</td>
</tr>
<tr>
<td>Dispatchable</td>
</tr>
<tr>
<td>Shunts</td>
</tr>
<tr>
<td>Branches</td>
</tr>
<tr>
<td>Transformers</td>
</tr>
<tr>
<td>Inter-ties</td>
</tr>
</tbody>
</table>

**Figure 6.4** System summary before applying the RED method on the case 8 network
Figure 6.5 Node and branch results before applying the RED method on the case8 network

After applying the RED method and conducting necessary adjustments, a new load flow calculation delivers the results in Figure 6.6 and Figure 6.7.
### System Summary

<table>
<thead>
<tr>
<th></th>
<th>How many?</th>
<th>How much?</th>
<th>P (MW)</th>
<th>Q (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>6</td>
<td>Total Gen Capacity</td>
<td>3.6</td>
<td>-0.2 to 1.1</td>
</tr>
<tr>
<td>Generators</td>
<td>3</td>
<td>On-line Capacity</td>
<td>3.6</td>
<td>-0.2 to 1.1</td>
</tr>
<tr>
<td>Committed Gens</td>
<td>3</td>
<td>Generation (actual)</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Loads</td>
<td>7</td>
<td>Load</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Fixed</td>
<td>7</td>
<td>Fixed</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Dispatchable</td>
<td>0</td>
<td>Dispatchable</td>
<td>-0.0 to -0.0</td>
<td>-0.0</td>
</tr>
<tr>
<td>Shunts</td>
<td>0</td>
<td>Shunt (inj)</td>
<td>-0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Branches</td>
<td>7</td>
<td>Losses ($I^2*Z$)</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Transformers</td>
<td>7</td>
<td>Branch Charging (inj)</td>
<td>-</td>
<td>0.0</td>
</tr>
<tr>
<td>Inter-ties</td>
<td>0</td>
<td>Total Inter-tie flow</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Areas</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Minimum**                               **Maximum**

| Voltage Magnitude | 0.956 p.u. @ bus 6 | 1.000 p.u. @ bus 1 |
| Voltage Angle    | -0.06 deg @ bus 4  | 0.00 deg @ bus 1  |
| P Losses ($I^2*R$) | -                | 0.01 MW @ line 1-2 |
| Q Losses ($I^2*X$) | -                | 0.00 MVAR @ line 1-2 |

**Figure 6.6** System summary after applying the RED method on the case8 network
When comparing the results, it can be deduced that the application of the RED method leads to the following benefits:

- Reduction of the active power losses in the network
- Reduction of the reactive power consumption on branches
- Reduction of the reactive power transmission in the network
- Improvement of the voltage profile (Figure 6.8)

In Figure 6.8, the blue (resp. green) line represents the voltage profile before (resp. after) the use of the RED method. The node numbers are given on the X-axis and the voltage (in Per-Unit) is given on the Y-axis.
6.2.3.2 Scenario in the case30 network and results

Suppose the case30 network in MATPOWER. The network has:

- a mesh structure,
- 30 nodes,
- 6 generators (connected at the nodes 1, 2, 13, 22, 23 and 27),
- 20 loads (none at the nodes 1, 5, 6, 9, 11, 13, 22, 25, 27 and 28),
- 41 branches and
- 2 shunts (at the nodes 5 and 24).

The network data are given in Appendix 15 and Figure 6.9 shows the network structure.

Figure 6.8 Voltage profiles before and after applying the RED method on the case8 network
The results in Figure 6.10, Figure 6.11 and Figure 6.12 obtained after running a load flow calculation on the network.
## System Summary

<table>
<thead>
<tr>
<th>How many?</th>
<th>How much?</th>
<th>P (MW)</th>
<th>Q (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>30 Total Gen Capacity</td>
<td>335.0</td>
<td>-95.0 to 405.9</td>
</tr>
<tr>
<td>Generators</td>
<td>6 On-line Capacity</td>
<td>335.0</td>
<td>-95.0 to 405.9</td>
</tr>
<tr>
<td>Committed Gens</td>
<td>8 Generation (actual)</td>
<td>196.0</td>
<td>121.2</td>
</tr>
<tr>
<td>Loads</td>
<td>20 Load</td>
<td>105.2</td>
<td>107.2</td>
</tr>
<tr>
<td>Fixed</td>
<td>20 Fixed</td>
<td>185.2</td>
<td>107.2</td>
</tr>
<tr>
<td>Dispatchable</td>
<td>0 Dispatchable</td>
<td>-0.0 of -0.0</td>
<td>-0.0</td>
</tr>
<tr>
<td>Shunts</td>
<td>2 Shunt (inj)</td>
<td>-0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Branches</td>
<td>41 Losses (I^2 * Z)</td>
<td>6.02</td>
<td>27.01</td>
</tr>
<tr>
<td>Transformers</td>
<td>0 Branch Charging (inj)</td>
<td>-</td>
<td>13.6</td>
</tr>
<tr>
<td>Inter-ties</td>
<td>7 Total Inter-tie Flow</td>
<td>32.7</td>
<td>69.4</td>
</tr>
<tr>
<td>Areas</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Magnitude</td>
<td>0.787 p.u. θ bus 15</td>
</tr>
<tr>
<td>Voltage Angles</td>
<td>-3.37 deg θ bus 15</td>
</tr>
<tr>
<td>P Losses (I^2 * R)</td>
<td>-</td>
</tr>
<tr>
<td>Q Losses (I^2 * X)</td>
<td>-</td>
</tr>
</tbody>
</table>

**Figure 6.10** System summary before applying the RED method on the case30 network
<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage</th>
<th>Generation</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mag (pu)</td>
<td>Ang (deg)</td>
<td>P (MW)</td>
</tr>
<tr>
<td>1</td>
<td>1.000</td>
<td>0.000°</td>
<td>30.35</td>
</tr>
<tr>
<td>2</td>
<td>0.948</td>
<td>0.433°</td>
<td>60.97</td>
</tr>
<tr>
<td>3</td>
<td>0.913</td>
<td>-0.506°</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>0.895</td>
<td>-0.575°</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.908</td>
<td>-0.952°</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0.877</td>
<td>-0.959°</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>0.879</td>
<td>-1.612°</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>0.862</td>
<td>-1.512°</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>0.832</td>
<td>-1.910°</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>0.809</td>
<td>-2.444°</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>0.832</td>
<td>-1.910°</td>
<td>-</td>
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<td>-</td>
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<td>-2.673°</td>
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<td>-3.367°</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>0.791</td>
<td>-5.233°</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
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<td>-2.000°</td>
<td>-</td>
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<td>0.793°</td>
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<td>-</td>
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<td>28</td>
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<td>-</td>
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<td>29</td>
<td>0.806</td>
<td>-0.855°</td>
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</tr>
<tr>
<td>30</td>
<td>0.793</td>
<td>-2.206°</td>
<td>-</td>
</tr>
</tbody>
</table>

**Figure 6.11** Node results before applying the RED method on the case30 network
After applying the RED method and conducting necessary adjustments, a new load flow calculation delivers the results in Figure 6.13, Figure 6.14 and Figure 6.15.
### System Summary

<table>
<thead>
<tr>
<th>How many?</th>
<th>How much?</th>
<th>P (MW)</th>
<th>Q (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>30</td>
<td>335.0</td>
<td>-95.0 to 405.9</td>
</tr>
<tr>
<td>Generators</td>
<td>6</td>
<td>335.0</td>
<td>-95.0 to 405.9</td>
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<tr>
<td>Committed Gens</td>
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<td>100.3</td>
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<tr>
<td>Loads</td>
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<td>189.2</td>
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<tr>
<td>Fixed</td>
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<td>189.2</td>
<td>107.2</td>
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<tr>
<td>Dispatchable</td>
<td>0</td>
<td>-0.0</td>
<td>0.0</td>
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<td>Shunts</td>
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<td>-0.0</td>
<td>0.2</td>
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<td>Branches</td>
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<td>9.21</td>
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<td>Transformers</td>
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<td>-</td>
<td>15.3</td>
</tr>
<tr>
<td>Inter-ties</td>
<td>7</td>
<td>32.4</td>
<td>19.4</td>
</tr>
<tr>
<td>Arcas</td>
<td>3</td>
<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Magnitude</td>
<td>0.945 p.u. @ bus 15</td>
</tr>
<tr>
<td>Voltage Angle</td>
<td>-3.85 deg @ bus 15</td>
</tr>
<tr>
<td>P Losses (I^2*R)</td>
<td>-</td>
</tr>
<tr>
<td>Q Losses (I^2*X)</td>
<td>-</td>
</tr>
</tbody>
</table>

**Figure 6.13** System summary after applying the RED method on the case30 network

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<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage</th>
<th>Generation</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>R (pu)</td>
<td>P (MW)</td>
<td>Q (MVAr)</td>
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<tr>
<td>1</td>
<td>1.000</td>
<td>26.04</td>
<td>13.77</td>
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<tr>
<td>2</td>
<td>0.594</td>
<td>60.97</td>
<td>26.87</td>
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<tr>
<td>3</td>
<td>0.975</td>
<td>-</td>
<td>-</td>
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<tr>
<td>4</td>
<td>0.970</td>
<td>-</td>
<td>-</td>
</tr>
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<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<td>8</td>
<td>0.949</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>0.962</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>0.963</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>16</td>
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<td>-</td>
<td>-</td>
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<td>0.954</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>0.985</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>0.963</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>29</td>
<td>0.965</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>0.953</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Total: 191.71 100.87 169.20 107.20

**Figure 6.14** Node results after applying the RED method on the case30 network
When comparing the results, it can be deduced that the application of the RED method leads to the following benefits:

- Reduction of the active power losses in the network
- Reduction of the reactive power consumption on branches
- Reduction of the reactive power transmission in the network
- Improvement of the voltage profile (Figure 6.16)

In Figure 6.16, the blue (resp. green) line represents the voltage profile before (resp. after) the use of the RED method. The node numbers are given on the X-axis and the voltage (in per-unit) is given on the Y-axis.

![Figure 6.16 Voltage profiles before and after applying the RED method on the case30 network](image)

### 6.3 Causer pays generation and load management approach for congestion and power flow management

As mentioned in Chapter 2, congestion and power flow problems are amongst problems encountered in networks since the beginning of the changes in the electrical power supply, and more particularly in distribution networks. These problems lead to a reduction of the network transmission capacity, to a restriction of the network operation, to possible damage of network components (e.g. lines, transformers) and cause costs to network operators. A new technically and economically efficient approach to solve

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these problems is presented, implemented and demonstrated in the following subsections.

Some network components (e.g. transformers) and connected consumers (e.g. motors) need inductive reactive power for operating. This reactive power is generated by the network and by some components such as generators and reactive power compensation units. Nevertheless, problems (e.g. congestions and voltage limit violations) and negative side effects (reduction of the network transmission capacity, increase of network losses, high voltage drops) could occur during power delivery. These problems restrict the network operation and cause costs to the network operator.

In this section, the current state of feed-in management in distribution networks is described (Subsection 6.4.1). A new and effective approach for feed-in management is presented (Subsection 6.4.2), the developed tool for feed-in management is demonstrated and the results are presented (Subsections 6.4.3 and 6.4.4).

6.3.1 State of the art of feed-in management

Nowadays in the Federal Republic of Germany, network operators can apply the following measures (in the following given order) to solve power flow and congestion problems in networks:

- **network-based measures** (tap position change of transformers, reactive power adjustments at generators and reactive power compensation units, and switchings of the network topology). For network operators, these measures are mostly free and cheaper compared to the market-based measures.
- **market-based measures** (balancing energy, redispatch of conventional generation plants, redispatch of renewable energy plants, load management). These measures are performed if the network-based measures were not sufficient to solve the problems.
- **forced adjustment measures** (redispatch of conventional generation plants, redispatch of renewable energy plants, load management). These measures are performed if both previous measures were not sufficient to solve the problems.

The redispatch of renewable energy plants, also considered as feed-in management, represents a temporary reduction of the power injection from renewable energy plants to
avoid or mitigate load flow problems in a network area until the expansion of the respective network area is completed [24, 25]. To perform a reduction, power reduction signals are sent to renewable energy plants (only wind turbines and photovoltaic systems). These plants react to the signal with a reduction of their power injection to the desired power level. The power reduction percentage signals 100%, 60%, 30% and 0% of the agreed connection power are currently applied in Germany. The “agreed connection power” refers either to the rated power of the plant or to a specified power between network operator and plant operator/owner.

According to the law [24, 25], this reduction should be performed without discrimination of plant operators/owners. In addition, “as many as necessary and as few as possible” plants should be involved. The operators/owners of the involved plant should be compensated by the network operator for the reduced amount of energy. These compensation costs are then paid by all grid consumers.

Currently, if some renewable energy plants are feeding into a congested network area, then a same reduction signal should be sent to all plants feeding into that respective area. Although this method is non-discriminatory, it does not always guarantee that “as many as necessary and as few as possible” plants are involved and it does not lead to the lowest compensation level.

Therefore, a new technically and economically efficient feed-in management approach is presented, implemented and demonstrated in the following subsections.

**6.3.2 New methodological approach**

The current network topology and the current network state are needed as initial input data set. The network state is obtained from a load flow calculation or through a network state estimation using the available measurements and substitute values.

First of all, network-based measures are applied to resolve the congestion. An attempt is made to optimize the reactive power flow in the network by adjusting the reactive power injections. Here, the RED (Relative Electrical Distance) method described in Section 6.2 is used.
In the real network operation, the mentioned adjustments can be performed periodically (due to load changes during the day) so as not to be carried out only after the occurrence of a network congestion.

If the congestion is not solved, an adjustment of the active power injection of generators is undertaken. The use of this measure on a plant is linked with a financial compensation for the unsupplied energy. To keep this compensation as low as possible, the following three questions need to be answered: How high is the contribution of each individual generator to the active power flow on the overloaded component (e.g. line, transformer)? Which generators should be adjusted? How high should be the adjustments of the active power supply of the generators selected for adjustment?

Determination of the contribution factors of each generator to the active power flow on the most overloaded component

A causality pays power flow tracing method [71] is used to determine the contribution factors. This method provides from the load flow calculation results and under consideration of the already performed reactive power adjustments, the active power contributions of each generator to the active power flow on a congested component (Equation 6.13).

\[
\begin{bmatrix}
P_{Lin} \\
Q_{Lin}
\end{bmatrix} =
\begin{bmatrix}
D_1^f \\
D_2^f \\
D_3^f \\
D_4^f
\end{bmatrix}
\begin{bmatrix}
P_{Gen}
\end{bmatrix}
\]

Equation 6.13

Since an optimization of the reactive power flow through adjustments of the reactive power injections was already performed and since it is now all about the influencing of the power flow on the line through adjustments of the active power injections, only the submatrix \( D_i^f \) from Equation 6.13 is used. The submatrix \( D_i^f \) containing the active power contribution factors of each generator to the active power flow on each line. \( D_i^f P_{Exc} \) from Equation 6.13 gives the active power injections of each generator to the active power flow on each line. However, the contribution factors of each generator to the active power flow on the lines are needed for the further analysis. These contribution factors are obtained by dividing the row values in the matrice \( D_i^f P_{Exc} \) by the respective column values in the vector \( P_{Lin} \). These contribution factors are used as input data for the computation of adjustment values.
Generator selection for the active power adjustments

Based on the signs of the contribution factors, it is first determined how the active power injection of each generator is with respect to the active power flow direction on the most congested component (same direction or opposite direction). The procedure is explained using Figure 6.17. Both the generators and the loads are included in the explanation of the selection process.

**Case I: CF & (Pt ≥ 0)**

- SF (Active power flow on the most congested line)
- SF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow on the most congested line)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow on the most congested line)

**Case II: SF & (Pt < 0)**

- SF (Active power flow on the most congested line)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow on the most congested line)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow on the most congested line)

**Case III: SF & (Pt ≥ 0)**

- CF (Active power flow on the most congested line)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow on the most congested line)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow on the most congested line)

**Case IV: CF & (Pt < 0)**

- CF (Active power flow on the most congested line)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- SF (Active power flow direction at the node)
- SF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow on the most congested line)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow direction at the node)
- CF (Active power flow direction at the secondary side of the transformer)
- CF (Active power flow on the most congested line)

**Figure 6.17** Network segment with renewable energy generation plants and loads

**Figure 6.17** shows a network segment with renewable energy generation plants and loads. Assume that the red marked line is overloaded. The active power on the line could flow in one of both directions indicated with the red marked arrows. Case A indicates an active power flow in the direction of the upper arrow and case B indicates an active power flow in the direction of the lower arrow.

**Case A.** According to the laws of physics, the active power contribution of generators on the right side of the congested line to the active power flow on that line could inevitably either be zero or be only in the same direction (symbol “SF” = Same Flow) as the active power flow on the congested line. The active power contribution of loads on the right side of the congested line to the active power flow on that line could inevitably either be zero or be only in the opposite direction (symbol “CF” = Counter Flow) to the active power flow on the congested line.

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The active power contribution of generators on the left side of the congested line to the active power flow on that line could inevitably either be zero or be only in the opposite direction (symbol “CF” = Counter Flow) to the active power flow on the congested line. The active power contribution of loads on the left side of the congested line to the active power flow on that line could inevitably either be 0 or be only in the same direction (symbol “SF”= Same Flow) as the active power flow on the congested line.

**Case B.** The active power contribution of generators on the right side of the congested line to the active power flow on that line could inevitably either be zero or be only in the opposite direction (symbol “CF” = Counter Flow) to the active power flow on the congested line. The active power contribution of loads on the right side of the congested line to the active power flow on that line could inevitably either be 0 or be only in the same direction (symbol “SF”= Same Flow) as the active power flow on the congested line.

The active power contribution of generators on the left side of the congested line to the active power flow on that line could inevitably either be 0 or be only in the same direction (symbol “SF” = Same Flow) as the active power flow on the congested line. The active power contribution of loads on the left side of the congested line to the active power flow on that line could inevitably either be 0 or be only in the opposite direction (symbol “CF”= Counter Flow) to the active power flow on the congested line.

From this analysis, a so-called “SC table” (Same Flow - Counter Flow table) is built for the considered congested network element.

If the active power contribution of a component (generator or load) to the active power flow on the considered congested network element is in the same direction (“SF”) as the active power flow on that network element, then a reduction of the active power of that component can effectively contribute to eliminate the congestion. If the active power contribution of a component (generator or load) to the active power flow on the considered congested network element is in the opposite direction (“CF”) to the active power flow on that network element, then an increase of the active power of that component can effectively contribute to eliminate the congestion.

Based on this fact, the possible components for the elimination of the congestion are now selected under consideration of the active power flow direction at the supplying transformer. Here, two possible situations must be distinguished.
Situation 1: Active power flows out of the network over the transformer (case II in case A and case IV in case B in Figure 6.17)

Consider case II in case A. Here the active power flow at the transformer has the same direction as the active power flow on the congested line. That means the transformer is marked as Same Flow “SF”. Now, all generators marked as “SF” and all loads marked as “CF” are selected as suitable components for the active power adjustment.

Consider case IV in case B. Here the active power flow at the transformer has an opposite direction to the active power flow on the congested line. That means the transformer is marked as Counter Flow “CF”. Now, all generators marked as “CF” and all loads marked as “SF” are selected as suitable components for the active power adjustment.

In Figure 6.17, the flow markings (“SF” or “CF”) of the selected components are marked in blue and the blue arrows indicate the power adjustment directions (active power increase or decrease).

Situation 2: Active power flows into the network over the transformer (case I in case A and case III in the case of B in Figure 6.17)

Consider case I in case A. Here the active power flow at the transformer has the opposite direction to the active power flow on the congested line. That means the transformer is marked as Counter Flow “CF”. Now, all generators marked as “SF” and all loads marked as “CF” are selected as suitable components for the active power adjustment.

Consider case III in case B. Here the active power flow at the transformer has the same direction as the active power flow on the congested line. That means the transformer is marked as Same Flow “SF”. Now, all generators marked as “CF” and all loads marked as “SF” are selected as suitable components for the active power adjustment.

In Figure 6.17, the flow markings (“SF” or “CF”) of the selected components are marked in blue and the blue arrows indicate the power adjustment directions (active power increase or decrease).

The next step consists in ranking on one side the generators and on the other side the loads, in descending order according to their contribution factors to the active power flow on the considered most congested component.
Determination of the active power adjustments of selected generators

For the determination, the active power sensitivity factors between the selected generators and the congested network component is computed based on Equation 6.14. Generators are retrieved one after another from the list of selected generators. The amount of active power adjustment at a generator is computed using the target active power change on the line and the active power sensitivity factor of the respective generator on the overloaded line under consideration of the generator capacity limit.

In Equation 6.15,

\[ \Delta P_{\text{Line}} \] represents the target active power change on the line,

\[ SF_{\text{Line}} \] is the active power sensitivity factor of the generator on the congested line,

\[ \Delta P_{\text{Gen}} \] is the active power adjustment to be carried out at the generator.

\[
\begin{bmatrix}
\Delta P_{\text{Line}} \\
\Delta Q_{\text{Line}}
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P_{\text{Line}}}{\partial P_{\text{Gen}}} & \frac{\partial P_{\text{Line}}}{\partial Q_{\text{Gen}}} \\
\frac{\partial Q_{\text{Line}}}{\partial P_{\text{Gen}}} & \frac{\partial Q_{\text{Line}}}{\partial Q_{\text{Gen}}}
\end{bmatrix}
\begin{bmatrix}
\Delta P_{\text{Gen}} \\
\Delta Q_{\text{Gen}}
\end{bmatrix}
\]

Equation 6.14

\[ \Delta P_{\text{Gen}} = \frac{\Delta P_{\text{Line}}}{SF_{\text{Line}}} \]

Equation 6.15

A load flow calculation is then performed to determine the achieved power flow changes on the line.

An update of the sensitivity factors, an update of the required active power changes on the congested component and the computation of the active power adjustments at the selected generators are performed as long as the congestion on the line is not resolved and all selected generators have not yet reached their limits. These actions are followed by a new load flow calculation.

If the congestion on the considered line is removed and if there are other congestions in the network, then the most congested network component is selected and the 3 described steps for active power adjustment are carried out.

6.3.3 Feed-in management tool

To demonstrate the capability of the approach, a tool was developed in Matlab [69]. This consists of the software package MATPOWER [70] for load flow calculation, the
developed Matlab program for feed-in management and interfaces (user interface, file interfaces) for input and output. A simplified top-level flow diagram of the tool is shown in Figure 6.18.

![Flow Diagram]

**Figure 6.18** Simplified top level flow diagram of the feed-in management tool

This tool not only allows a network operator to perform a power flow and congestion management in its own network, but also to conduct these on behalf of the upstream network operator (e.g. TSO) as described in Section 3.3. After some modifications, this tool can also be optimally used for scheduling management (respectively for active and reactive power).
6.3.4 Scenario

A congestion event due to weather and maintenance work is simulated in a low voltage network.\(^1\) Then 3 different adjustment strategies are applied for decongesting the network. At the end, the effort for coping the network congestion, the number of adjusted plants, the total amount of adjusted active and reactive power, and the resulting compensation costs are compared.

**Figure 6.19** shows the considered low voltage network. In this network, only renewable energy generation plants are present.

![Diagram of Low Voltage Network](image)

**Figure 6.19 Low voltage network**

After a weather forecast for the next day (Outcome: Little infeed from renewable energy generation plants) and a network state forecast (Outcome: Network status OK), the network operator decides to carry out maintenance work on line 8 on the next day. The switchings are carried out and the new state of the network topology is as shown in **Figure 6.20**.

\(^1\) Only data of a low voltage network were available at the implementation time. Of course the method can be applied to other network distribution levels.
The weather situation changes suddenly during the maintenance work, the renewable energy generation plants feed more power than predicted into the grid and as consequence, the red-marked network segment (Figure 6.20) gets overloaded. The following strategies are used to eliminate the congestion:

- **Strategy 1**: Percentage power reduction in large steps (100%, 60%, 30%, 0% of $P_t$) of all plants in the overload area. This is the current feed-in management strategy in Germany.
- **Strategy 2**: Use of the developed method
- **Strategy 3**: Use of the developed method in small steps (e.g. 10% of $P_t$)

The simulation results will be presented. The figures shown are for:

- **Lines**: their capacity limits (named “Max”), their loadings before the use of the strategies (“From load flow calculation”), after the reactive power flow adjustment (“After RED”, applied only in strategies 2 and 3) and after the active power adjustment (“After active power adjustment”)
- **Generators**: their active and reactive power limits (“Max” and “Min”), the active and reactive power injections before the use of the strategies (“From load flow calculation”).

**Figure 6.20** Low voltage network after the switchings
calculation”), after the reactive power flow adjustment (“After RED”, applied only in strategies 2 and 3) and after the active power adjustment (“After active power adjustment”)

The figures with the simulation results from strategy 3 are not displayed. The results can be directly derived from the results from strategy 2. All the results are compared in Subsection 6.3.5. It is important to mention that the loads were not affected (active and reactive power) during the use of all these strategies.

6.3.4.1 Strategy 1 (current method)

A percentage power reduction in large steps (100%, 60%, 30%, 0% of $P_r$) of all plants in the overloaded area is performed in this strategy. The transmission of the signal “60% of $P_r$” to all 9 generators at the nodes 9 to 25 could not eliminate the overload. The signal “30% of $P_r$” could get the line loadings below the respective line capacity limits (Figure 6.21). Figure 6.22 shows that the active power infeeds of 6 generators were influenced during the measure. The reason resides in the fact that the 3 other generators have each an active power infeed into the grid lying below 30% of their respective rated power. These are the generators connected to the nodes 9, 16 and 17.
**Figure 6.21** Apparent powers on lines

**Figure 6.22** Active powers of generators
6.3.4.2 Strategy 2 (new method)

In this strategy (new approach), an adjustment of the reactive power flow in the network using the RED method is first performed. It can be seen in Figure 6.23 that this adjustment leads to a reduction of the line loadings. The reactive power variations of the generators after the adjustment are visualized in Figure 6.25. Since the congestion is still present, an active power adjustment is performed. For this adjustment, the generator at node 19 is selected by the tool. The active power infeed is reduced by 74.321 kW. Now, only 25.679% of $P_r$ are fed (Figure 6.24).

![Figure 6.23 Apparent powers on lines](image-url)
Figure 6.24 Active powers of generators

Figure 6.25 Reactive powers of generators
6.3.4.3 Strategy 3 (new method with 10% steps)

This strategy is identical to strategy 2, but here a percentage power reduction of 10% of $P_r$ per step is applied on generators. Strategy 2 suggested that the generator at node 19 must feed only 25.679% of $P_r$ to eliminate the overload (Figure 6.24). Therefore, in case of a percentage power reduction of 10% of $P_r$ per step, the generator must feed 20% of $P_r$ into the grid to eliminate the congestion.

6.3.5 Results

Table 6.1 contains a comparison of the 3 strategies. The strategies 2 and 3 (both from the new approach) require a reduction of the active power infeed of only one generator to eliminate the congestion. Thereby, the total active power adjustments are much smaller than when using strategy 1 (current method). In strategy 1, 9 plants are involved in the power adjustment procedure, but the active power injections of only 6 are adjusted.

Particular attention should be paid to the results of the strategy 1 and 2. Due to the reactive power flow adjustment in the network, only less than half of the active power adjustment as necessary in strategy 1 is needed in strategy 2. This is equivalent to almost a halving of the compensation costs to be paid.

<table>
<thead>
<tr>
<th>Number of adjusted generators</th>
<th>Total active power adjustment [kW]</th>
<th>Signal for active power adjustment [% of $P_r$]</th>
<th>Total compensation costs for the active power adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 1 (current method in Germany)</td>
<td>6</td>
<td>-160</td>
<td>30</td>
</tr>
<tr>
<td>Strategy 2 (new method)</td>
<td>1</td>
<td>-74.321</td>
<td>25.679</td>
</tr>
<tr>
<td>Strategy 3 (new method with 10% steps)</td>
<td>1</td>
<td>-80</td>
<td>20</td>
</tr>
</tbody>
</table>
The advantages of the new method for a network operator are:

- Simplification of the billing process which becomes manageable.
- Reduction of the efforts for power adjustment, since only a few plants are adjusted. Only the plants with the greatest impact on the network congestion are adjusted.
- Cost reduction: An active power adjustment to a lesser extent compared with the current adjustment strategy. Based on the amount of energy not supplied, this means a significant reduction of compensations.
- Better network management.
- Creation of a legal basis to prove the need for the adjustment of selected plants. The decision on the adjustment measures is based on a causer pays power flow tracing method.

On a social level, these results have a very positive impact on the electricity bills (less contribution for compensation costs) and on the acceptance of the energy revolution (“Energiewende”).

6.4 Topology-based generation and load adjustment for voltage management

As mentioned in Section 2.4, voltage increases at network nodes occur due to high power infeed of renewable energy plants while voltage drops are caused by high power consumption of loads in distribution networks. Thereby, the occurrence of voltage range violations and other voltage problems is more frequent. To prevent or eliminate these problems, voltage management is applied. In this section, the current state of voltage management in distribution networks is described (Subsection 6.4.1). A new and effective approach for voltage management is presented (Subsection 6.4.2), the developed tool for voltage management is demonstrated and the results are presented (Subsections 6.4.3 and 6.4.4).
6.4.1 State of the art of the voltage management in distribution networks

Nowadays voltage problems in distribution networks are not registered in the control center due to the lack of infrastructures (information and communication resources, measurement devices). But in the case of the identification of voltage problems in medium voltage networks, a tap adjustment of the feed-in HV/MV transformer is mainly carried out. However, this action affects the voltages at all network nodes and as well as the voltages in the low voltage networks connected to the medium voltage network over MV/LV transformers. Another measure consists in changing the network topology. This measure is not particularly preferred due to some specific network operational reasons, but can be applied. Reactive power compensation units are also used mainly to support the voltage by means of reactive power. This measure does help, but is not very effective as described in Subsection 2.4.3.1 with respect to voltage problems in distribution networks.

In the next subsection, a new approach for efficient voltage management is presented.

6.4.2 New methodological approach

The current network topology and the current network state are needed as initial input data set. The network state is obtained from a load flow calculation or through a network state estimation using the available measurements and substitute values.

First of all, network-based measures are applied to resolve the voltage violation. An attempt is made to optimize the reactive power flow in the network by adjusting the reactive power injections. Here, the RED (Relative Electrical Distance) method described in Section 6.2 is used.

In the real network operation, the mentioned adjustments can be performed periodically (due to load changes during the day) so as not to be carried out only after the occurrence of a voltage limit violation in the network.

If the voltage limit violation is not solved, an adjustment of the active power injection of generators is undertaken. The use of this measure on a plant can lead to a compensation of the plant operator/owner for the reduced amount of energy. A major goal in the active power adjustment would be to maintain this compensation as minimal as possible.
For that, the following two steps are performed:

Determination of the node with the greatest voltage limit violation

Hereby the node having the greatest voltage limit violations (highest overvoltage and lowest undervoltage) are first of all determined based on the node voltage values.

Generation selection for adjustment\(^2\)

Initially it is determined if a generator with controllable active power output is connected at the node with the greatest voltage limit violation. If this is the case, the active power of that generator is gradually adjusted (e.g. by 5% of P\(_t\)) under consideration of its active power limit until this limit is reached. After each adjustment, a load flow calculation is performed. This is followed by a check if the voltage problem is solved and if an active power limit of the generator is reached. This is done iteratively until either an active power limit of the generator is reached or the voltage problem is solved.

If no generator with controllable active power output is connected at the node with the highest voltage limit violation or the active power limit of a connected controllable generator at this node is reached, then the topologically closest generator with controllable active power output to the node with the highest voltage limit violation is determined. For this, the RED method is used. If one is found, the active power of that generator is gradually adjusted (e.g. by 5% of P\(_t\)) under consideration of its active power limit until this limit is reached. After each adjustment, a load flow calculation is performed. This is followed by a check whether the voltage problem is solved and whether the active power limit of the generator is reached. This is done iteratively until either the active power limit of the generator is reached or the voltage problem is solved.

If the voltage problem at the selected node is solved and there are other voltage limit violations in the network, then the two steps (“determination of the node with the greatest voltage violation” and “generation selection for adjustment”) are again performed. This is done until all voltage violations are solved or till no further adjustments can be performed on selected generators.

\(^2\) The use of the transformer tap position as option for solving voltage problems in networks was yet not considered, but it can be easily integrated in the presented approach.

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If no generator with controllable active power output is found, then no action is undertaken. At the end of the execution of the program, the results are displayed.

6.4.3 Tool for voltage management

To demonstrate the ability of the approach, a tool was developed in Matlab [69]. This consists of the software package MATPOWER [70] for load flow calculation, the developed Matlab program for voltage management and interfaces (user interface, file interfaces) for input and output. A simplified top-level flow diagram of the tool is shown in Figure 6.26.
Figure 6.26 Simplified top level flow diagram of the voltage management tool
6.4.4 Scenario and results

Figure 6.27 illustrates the considered medium voltage network.

An undervoltage situation is created in the network by increasing the consumption of the load connected at node 6 from 0.1 MW to 1.1 MW. The loads have a power factor of 0.97 reactive. In order to solve this problem, the tool proposes adjustments of the active and reactive power infeeds of generators. The results are shown below in Figure 6.28, Figure 6.29 and Figure 6.30.

Figure 6.28 Network voltage profile
It can be seen that the network voltage profile is brought back in the allowed voltage range (±10% of the nominal voltage). As the whole reactive power produced by the generators is not absorbed by the components in the network, there is a reactive power flow reversal occurring at the transformer.
6.5 Network state estimation in distribution grids by lack of measurements

As mentioned in Subsection 2.4.3.4, monitoring of distribution networks should be provided to ensure reliable, safe and efficient network operation due to the new dynamics in these networks. This is achieved through the installation in the network of information and communications infrastructures, sensors and measurement devices. Given the usual configuration of distribution networks, an installation of measuring devices and sensors at all nodes and in all branches would cause high costs. Therefore, technical solutions are necessary to achieve the observability of distribution networks with the lowest possible number of measurements/sensors and at reasonable cost.

6.5.1 State of the art of the state estimation in distribution networks

Nowadays, relatively few measurement devices and sensors are installed in distribution networks. The most frequently used state estimation algorithm (Weighted Least Squared method) in transmission networks cannot be applied in distribution networks as this algorithm requires an overdetermined system of linear equations. Due to the lack of measurements in distribution networks, typically an underdetermined system of linear equations applies.

The rollout of smart metering systems in distribution networks will extend over many years. Until the full completion of the rollout is achieved, these networks will remain unobservable. Figure 6.31 shows the transition from a conventional grid system over a transitional system to a completely metered system.
The major stages of distribution grids during this transition will be:

- Distribution grids as “conventional systems”: No smart meters are installed at connected units in distribution grids. A state estimation algorithm should be able to provide approximate estimation of the network state using measurements at the feed-in transformer, pseudo data, virtual data, replacement values, load profiles and generation profiles.

- Distribution grids as “transitional systems”: Smart meters are installed at some of the units. With real-time measurements coming in from these smart meters, a state estimation algorithm should be able to correct the gathered measurements and to provide good estimations of missing values.

- Distribution grids as “smart metered systems”: All units in the distribution grids are measured using smart meters. A state estimation algorithm should be able to identify eccentric measurements which may be due to measurement errors or measurement manipulations, to give hints in case of manipulations, to do corrections in case of measurement errors and to provide good estimations of missing values in case of breakdowns of some smart meters.

Currently existing state estimation algorithms do not run at all or well in these three frameworks mostly due to special conditions which prevail, to the lack of necessary direct measurements and to the lack of required number of measurements. Therefore the development of a suitable state estimator to handle the cases shown in Figure 6.31 is required.
The WLS method (Weighted Least Squared) method is now considered to illustrate some restrictions of current estimators. Although the WLS algorithm is a well tested and widely used algorithm, it is unsuitable for the problem statement as it requires that an overdetermined set of equations to be formed before it can be applied. As the problem statement initially starts with no measurements, this algorithm may be rendered unusable. It hence becomes necessary to use an algorithm that may overcome the requirement for a large number of measurements before estimation.

The WLS Estimator deals with the time invariant case in which state estimates are obtained from a single scan of measurements. It was referred to as a static estimator as it does not consider any past information about the system state during the estimation process [72, 73, 74]. On one side, this is an advantage when computing the estimate, as design of the mathematical model becomes less complicated and less costly. On the other side, this represents a disadvantage as one tends to give no importance to valuable information from the past that may increase the accuracy of the estimation process.

6.5.2 New methodological approach

6.5.2.1 Kalman Filter

The use of a Kalman filter for state estimation consists of predicting the behaviour of the system in a particular state, and then comparing that behaviour with the inputs and the outputs of the real system to determine which state or states the system is most likely to take. It is a dynamic estimator since it estimates the state from a time sequence of snapshots of system measurements. The estimation process is recursive and takes into account past information. This was referred to as a tracking state estimator by Schweppe in [72, 73, 74] and later discussed and developed by Atif. E. Larson et al in [75].

Due to its properties, it is chosen as an appropriate method to handle the grid stages mentioned in Subsection 6.5.1. The Kalman filter must be adjusted to meet the requirements of the three stages (Subsection 6.5.1) and will integrated in the new state estimation approach. A brief introduction to Kalman filtering can be found in the Appendix 1.
The complex node voltage and node power values are considered as possible state values. In order to use the Kalman filter in power grid systems, the nonlinear load flow equations must be linearized.

The state vector of the Kalman filter is defined as follows:

\[ \mathbf{x} = [\delta_1 \ldots \delta_n, V_1 \ldots V_n, P_1 \ldots P_n, Q_1 \ldots Q_n]^T \]  \hspace{1cm} \text{Equation 6.16}

where,
\( \mathbf{x} = \) State vector
\( \delta = \) Node voltage angle
\( V = \) Node voltage magnitude
\( P = \) Node active power
\( Q = \) Node reactive power

The measurement vector is as follows:

\[ \mathbf{z} = [P_{\text{transformer}} \ldots Q_{\text{transformer}}, \delta_1 \ldots \delta_n, V_1 \ldots V_n, P_1 \ldots P_n, Q_1 \ldots Q_n]^T \]  \hspace{1cm} \text{Equation 6.17}

where,
\( \mathbf{z} = \) Measurement vector
\( P_{\text{transformer}} = \) Active power at the transformer
\( Q_{\text{transformer}} = \) Reactive power at the transformer

The ideal measurement values are overlaid with abnormally distributed noise

\[ \mathbf{z} = h(\mathbf{x}) + \mathbf{v} \]  \hspace{1cm} \text{Equation 6.18}

where,
\( h = \) Measurement function
\( v = \) Measurement noise

The measurement matrix is defined as follows:

\[ \mathbf{H} = \frac{\partial h(\mathbf{x})}{\partial \mathbf{x}} \]  \hspace{1cm} \text{Equation 6.19}

The inputs of the Kalman filter:

\[ \mathbf{u} = [\Delta P_1 \ldots \Delta P_n, \Delta Q_1 \ldots \Delta Q_n, \Delta P_1 \ldots \Delta P_n, \Delta Q_1 \ldots \Delta Q_n]^T \]  \hspace{1cm} \text{Equation 6.20}

where,
\( \mathbf{u} = \) Input vector
\[ \Delta = \text{Variation between measurement scanning steps} \]

The sum of all powers at each node is zero.

\[ g_i(x, u) = V_i \cdot e^{j\delta_i} \sum_k (Y_{ik} \cdot V_k \cdot e^{j\delta_k})^* - (P_i + jQ_i) = 0 \]  \hspace{2cm} \text{Equation 6.21}  \\

\[ f(x, u) = [f_p(x, u) f_q(x, u)] = [\text{real}(g_i(x, u) \ldots g_n(x, u)) \ \text{imag}(g_i(x, u) \ldots g_n(x, u))]^T \]  \hspace{2cm} \text{Equation 6.22}  \\

To perform an estimation, the nonlinear load flow \textbf{Equation 6.22} has to be linearized at the operating point.

\[ \frac{\partial f(x, u)}{\partial x} \Delta_x + \frac{\partial f(x, u)}{\partial u} \Delta_u + e_r = 0 \]  \hspace{2cm} \text{Equation 6.23}  \\

where,

\[ e_r = \text{Modelling error due to linearization of nonlinearity} \]

\[ \frac{\partial f(x, u)}{\partial x} = \begin{pmatrix} \frac{\partial f_p}{\partial \delta} & \frac{\partial f_p}{\partial V} \\ \frac{\partial f_q}{\partial \delta} & \frac{\partial f_q}{\partial V} \end{pmatrix} = J, \text{ with } J \text{ representing the power flow Jacobian matrix} \]  \hspace{2cm} \text{Equation 6.24}  \\

\[ \frac{\partial f(x, u)}{\partial u} = \begin{pmatrix} \frac{\partial f_p}{\partial \delta} & \frac{\partial f_p}{\partial V} \\ \frac{\partial f_q}{\partial \delta} & \frac{\partial f_q}{\partial V} \end{pmatrix} = \begin{pmatrix} I & 0 \\ 0 & I \end{pmatrix} = I, \text{ with } I \text{ representing the unity matrix} \]  \hspace{2cm} \text{Equation 6.25}  \\

The following equation is obtained from \textbf{Equation 6.23}.

\[ x_{k+1} = x_k + J^{-1} [u_{k+1} - u_k] + w_k \]  \hspace{2cm} \text{Equation 6.26}  \\

where,

\[ w_k = \text{linearization error} \]

The next following four processing steps are repeated in each iteration.

1) \textbf{Prediction}  

The linearized power flow equation is used. The system state is updated.

\[ x_{k+1} = x_k + J^{-1} [u_{k+1} - u_k] + w_k \]  \hspace{2cm} \text{Equation 6.27}  \\

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2) Calculation

The Kalman gain is calculated next.

\[ K_{k+1} = [P_k + J^{-1} \cdot S_w \cdot (J^{-1})^T \cdot H^T \cdot [H \cdot [P_k + J^{-1} \cdot S_w \cdot (J^{-1})^T \cdot H^T + S_v]^{-1} \]

**Equation 6.28**

3) Update State Estimation

The system state is corrected by the Kalman gain.

\[ \hat{x}_{k+1} = \tilde{x}_{k+1} + K_{k+1} \cdot [z_{k+1} - h \cdot \tilde{x}_{k+1}] \]

**Equation 6.29**

4) Update Covariance Matrix

Now, the covariance matrix is updated. This indicates the accuracy of the estimate.

\[ P_{k+1} = [I - K_{k+1} \cdot H] \cdot [P_k + J^{-1} \cdot S_w \cdot (J^{-1})^T \cdot [I - K_{k+1} \cdot H]^T + K_{k+1} \cdot S_v \cdot K_{k+1}^T \]

**Equation 6.30**

The Kalman Filter satisfies two major criterions [76]:

- The average value of the state estimate is equal to the average value of the true state. Mathematically it is expressed as \( E(\hat{x}) = E(x_{true}) \), the expected value of the state estimate is equal to the expected value of the true state.
- The state estimate must be as close to the true state as possible, i.e. an estimate with the smallest possible error variance is required.

The concept of Kalman filtering in electrical power system state estimation is prevalent. It has been a topic discussed right from the conceptualization of state estimation in electrical power systems in 1970 [72, 73, 74] and has been also implemented since 1972 [7, 77]. The algorithm seems to allow good flexibility in choosing mathematical models for measurements and for state transition, a convenient method of choosing or changing error covariances and most importantly providing good results. It would be a good match for the problem statement in **Subsection 6.5.1**.
6.5.2.2 Problem Formulation

The adaptation of the Kalman Filter algorithm is performed in the following subsections. For explanation purpose, a Micro Grid will be considered as network.

6.5.2.2.1 State Definition

The state vector is supposed to be able to show the information of the system in a condensed form so that it would be possible to take accurate control decisions by just referring to only the state of the system. Depending on the available measurements, the definition of the state can be modified to include:

- Voltage angle of every unit node
- Voltage magnitude of every unit node
- Active power injection of every unit node i.e. the difference between active power consumed and active power generated, \( P_i = P_{\text{Demand}} - P_{\text{Generated}} \)
- Reactive power injection of every unit node i.e. the difference between reactive power consumed and reactive power generated, \( Q_i = Q_{\text{Demand}} - Q_{\text{Generated}} \)

The state vector is already given by Equation 6.16. From the state vector, the state transition equation is defined as explained in [75]:

\[
x_{k+1} = x_k + \Delta x + w
\]

Equation 6.31

where \( w \) is considered to be a white noise process as explained in [75]. Hence, from this it can be inferred that

\[
\Delta x = [\Delta \delta_1 \Delta \delta_2 ... \Delta \delta_n \Delta V_1 \Delta V_2 ... \Delta V_n \Delta P_1 \Delta P_2 ... \Delta P_n \Delta Q_1 \Delta Q_2 ... \Delta Q_n]^T
\]

Equation 6.32

To obtain \( x \), the results obtained by [78] are very important for the computational improvement of the total estimation algorithm. \( u_k \) is considered to be:

\[
u_k = [\Delta P_1 \Delta P_2 ... \Delta P_n \Delta Q_1 \Delta Q_2 ... \Delta Q_n \Delta V_1 \Delta V_2 ... \Delta V_n]^T
\]

Equation 6.33

This includes the second term of the Equation 6.26 within \( u_k \).

Hence, using Equations 6.24 and 6.26, the B matrix is obtained:

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\[
B = \begin{pmatrix} J^{-1} & 0 \\ 0 & I \end{pmatrix}
\]

**Equation 6.34**

The total state equation can be written as:

\[
\begin{pmatrix}
\delta_{1}^{k+1} \\
\delta_{2}^{k+1} \\
\vdots \\
\delta_{n}^{k+1}
\end{pmatrix}
= \begin{pmatrix}
\delta_{1}^{k} \\
\delta_{2}^{k} \\
\vdots \\
\delta_{n}^{k}
\end{pmatrix} + \begin{pmatrix} J^{-1} & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix}
\Delta P_{1}^{k} \\
\Delta P_{2}^{k} \\
\vdots \\
\Delta P_{n}^{k} \\
\Delta Q_{1}^{k} \\
\Delta Q_{2}^{k} \\
\vdots \\
\Delta Q_{n}^{k}
\end{pmatrix} + w^{k}
\]

**Equation 6.35**

Here, 
\( J^{-1} \) is the inverse of the power flow Jacobian matrix, 
\( w^{k} \) is the process error due to the inputs.

The process error covariance matrix is exactly defined as mentioned in **Equation A1.3** in **Appendix 1**.

\[
S_{w} = E(w_{w} w_{w}^{T})
\]

**Equation 6.36**

### 6.5.2.2.2 System measurements

The measurement vectors for each stage (as discussed in **Subsection 6.5.1**) during the transition are considered as follows.

- Stage 1 (no smart meters are present in the grid): The measurements from the MV/LV transformer are considered as only direct measurements as there would
be no other measurements within the grid. The measurement vector for the first case could be expressed as:

\[ z = [P_{\text{transformer}} \ Q_{\text{transformer}}]^T \]  

Equation 6.37

- Stage 2 (some smart meters are present in the grid): These measurements are integrated in the measurement vector to obtain much better state estimates of the system than in the first stage. Hence the measurement vector for the second case could be expressed as:

\[ z = [P_{\text{transformer}} \ Q_{\text{transformer}} \ \delta_a \ \delta_b \ \ldots \ V_a V_b \ \ldots \ P_a P_b \ \ldots \ Q_a Q_b \ \ldots]^T \]  

Equation 6.38

- Stage 3 (all smart meters are installed in the grid): It hence seems only appropriate to use all the measurements available to find a state estimate. The measurement vector for the third case could be expressed as:

\[ z = [P_{\text{transformer}} \ Q_{\text{transformer}} \ \delta_a^1 \ \delta_a^2 \ \ldots \ V_1 V_2 \ \ldots \ P_1 P_2 \ \ldots \ Q_1 Q_2 \ \ldots]^T \]  

Equation 6.39

The measurement model would be expressed in the same form as Equation A1.2 in Appendix 1:

\[ z = h(x) + v \]  

Equation 6.40

6.5.2.2.3 Approximate Measurement Model

A linearized version of the exact measurement model (given and explained in Appendix 2) is presented here.

a For Micro Grid without Smart Meters

Since the output parameters in Equation 6.37 are only \( P_{\text{transformer}} \) and \( Q_{\text{transformer}} \), it can be considered that both parameters are a linear weighted combination of the active and reactive power injections of each individual unit in the grid. Thus, the output equation for the case in Figure 6.31a is:
where $C_{P_{\text{transformer}}}$ and $C_{Q_{\text{transformer}}}$ are the scalar coefficients that weighs the contributions of each unit's active and reactive power injections to the transformer powers. These are left to be scalar coefficients. Unit generations and consumptions in the grid have an effect on these coefficients. These coefficients can be determined at each sampling step by using a variant of the function for determining the contribution factors of each unit to the active power flow on the most overloaded component as described for the approach in Section 6.3. But here it would be rather applied for determining the contribution factors of each unit to the active and reactive power flow on the feed-in transformer.

b  For Micro Grid with Smart Meters

As the system moves into the case shown in Figure 6.31b, the model expressed by the state transition Equation 6.35 remains the same. The measurement or output equation, Equation 6.41, will have more measurement variables added to the measurement vector. The number of variables would depend upon the number of measurements.

$$z = [P_{\text{transformer}}, Q_{\text{transformer}}, \delta_a, \delta_b, \ldots, V_a, V_b, \ldots, P_a, P_b, \ldots, Q_a, Q_b, \ldots]^T$$  

Equation 6.42

where $a, b, \ldots < m$. Hence the output equation then becomes:
Here the rows which are denoted by dots are zero rows. Some measurements which are acquired directly represent the state of the power system.

Eventually, as the number of smart meters increase within the system as shown in Figure 6.31c, the output vector for these measurement variables would be expressed as:

$$
\begin{bmatrix}
  P_{\text{transformer}} \\
  Q_{\text{transformer}} \\
  \delta^k_a \\
  \delta^k_b \\
  \vdots \\
  V^k_a \\
  V^k_b \\
  \vdots \\
  p^k_a \\
  p^k_b \\
  \vdots \\
  Q^k_a \\
  Q^k_b \\
  \vdots \\
  0 \\
\end{bmatrix}
\begin{bmatrix}
  0 & \cdots & 0 & \cdots & C_{P_{\text{transformer}}} & \cdots & 0 \\
  0 & \cdots & 0 & \cdots & 0 & \cdots & C_{Q_{\text{transformer}}} \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  0 & \cdots & 1 & \cdots & 0 & \cdots & 0 \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  0 & \cdots & 0 & \cdots & 1 & \cdots & 0 \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  0 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\
\end{bmatrix}
= 
\begin{bmatrix}
  \delta^k_1 \\
  \delta^k_2 \\
  \vdots \\
  \delta^k_a \\
  \delta^k_b \\
  \vdots \\
  V^k_1 \\
  V^k_2 \\
  \vdots \\
  V^k_a \\
  V^k_b \\
  \vdots \\
  p^k_1 \\
  p^k_2 \\
  \vdots \\
  p^k_a \\
  p^k_b \\
  \vdots \\
  Q^k_1 \\
  Q^k_2 \\
  \vdots \\
  Q^k_a \\
  Q^k_b \\
  \vdots \\
  0 \\
\end{bmatrix}
+ \begin{bmatrix}
  \delta^k_1 \\
  \delta^k_2 \\
  \vdots \\
  \delta^k_a \\
  \delta^k_b \\
  \vdots \\
  V^k_1 \\
  V^k_2 \\
  \vdots \\
  V^k_a \\
  V^k_b \\
  \vdots \\
  p^k_1 \\
  p^k_2 \\
  \vdots \\
  p^k_a \\
  p^k_b \\
  \vdots \\
  Q^k_1 \\
  Q^k_2 \\
  \vdots \\
  Q^k_a \\
  Q^k_b \\
  \vdots \\
  0 \\
\end{bmatrix}
$$

Equation 6.43
where $I$ is the identity matrix.

6.5.3 Tool for state estimation

To demonstrate the capability of the approach, a tool was developed using Matlab [69]. This consists of the software package MATPOWER [70] for load flow calculation, the Matlab program developed for the state estimation and interfaces (user interface, file interfaces) for input and output. A simplified top-level flow diagram of the tool is shown in Figure 6.32.
Figure 6.32 Simplified top-level flow diagram of the tool for demonstrating the developed state estimation algorithm

The tool consists of 4 layers:

- **1st layer**: the first layer is used to create a “synthetic real world”. A load flow calculation is performed on a given network model and all results (node voltage magnitudes, node voltage angles, active and reactive power at nodes, active and reactive power on branches) are stored. These quantities represent the real and non-noisy physical quantities that are present in the network (it is assumed that the network model is very precise and detailed). The load flow calculation is performed with the software package “MATPOWER” under use of the integrated Newton-Raphson method. This layer is executed only once over the entire simulation time interval under consideration of the set sample time interval. All results are stored at the end.

- **2nd layer**: at all points where measurements are to be made in the considered network, the respective measurements are taken from the computed results of the 1st layer and modified with a normally distributed noise. The result represents a simulation of the measured and noisy physical quantities from the installed measurement systems. It is important to mention that any number of measurement points can be selected with the corresponding measurement types
(node voltage magnitude, node voltage angle, active and reactive power at nodes, active and reactive power on branches). This layer is executed only once over the entire simulation time interval under consideration of the set sample time interval. All results are stored at the end.

- 3rd Layer: This layer contains the developed state estimation algorithm. Here a reconstruction of unmeasured quantities is first performed followed by an estimate of the system state using the Kalman filter. The goal is to obtain a realistic possible network state (in this case, the “synthetic real world”) as a result. For the reconstruction of the possible missing quantities, two methods are available.

In the first method, the difference between the measured power at the transformer feed-in point and the sum of the measured node powers is determined. This power difference is distributed equally on all unmeasured nodes.

\[
P_r = P_{\text{inf}} - \sum_{N_{\text{measured \_ nodes}}} P_{\text{measured \_ nodes}} \tag{Equation 6.45}
\]

\[
Q_r = Q_{\text{inf}} - \sum_{N_{\text{measured \_ nodes}}} Q_{\text{measured \_ nodes}} \tag{Equation 6.46}
\]

For the reconstruction, this method assumes an equal loading at the unmeasured nodes. Then an approximate network state is determined by means of a load flow calculation under consideration of the computed quantities.

In the second method, profiles (generation profile, consumption profile) are considered for unmeasured nodes. These profiles can be obtained from historical data or from a forecast. An approximate network state is determined by means of a load flow calculation under consideration of the node power consisting of measurements (at measured nodes) and scaled profiles (at unmeasured nodes).

It is expected that this method provides better results.

After the reconstruction with one of the two methods and based on the determined approximate network state, the Kalman filter is applied to obtain the network state much closer as possible to the realistic network state (state in the
“synthetic real world”). The Kalman filter runs iteratively over the entire simulation time interval under consideration of the set sample time interval. The unmeasured quantities are adjusted so that the resulting estimates physically fit with the measured variables. Parallel to this, a filtering of noise from the measured quantities is performed.

\[
P_m, Q_m \\ \text{Reconstruction of measurements} \\ P_m, Q_m \\ \text{Load flow computation} \\ P_e, Q_e \\ \text{Kalman filter}
\]

**Figure 6.33** Reconstruction of missing measurements by means of load and generation profiles

- 4\textsuperscript{th} layer: A detection and correction of measurement outliers is performed in this layer. Measurement outliers can be detected if the difference between the estimated and the measured value of a quantity is a large multiple of the standard deviation. In this instance, a multiplier of 10 is used.

\[
(P_m - P_e) > (\sigma_P \cdot 10)^2 \\
(Q_m - Q_e) > (\sigma_Q \cdot 10)^2
\]

**Equation 6.47**

**Equation 6.48**

The last correct measurement value is considered as valid during the correction of measurement outliers. Then a new state estimation with the corrected measurements is made. This layer is executed only once over the entire simulation time interval under consideration of the set sample time interval. All results are stored at the end.

**Figure 6.34** shows the graphical user interface of the tool. A detailed description of the operation can be found in the supervised project [8].

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6.5.4 Scenarios and results

In this section, different scenarios are performed. A low voltage network of the DSO Vorarlberg Netz in Austria is taken as network model. Figure 6.35 shows the network structure with the loads, the lines, the local substation transformer and an installed PV system. The network consists of 70 nodes.

The following legend in Table 6.2 explains the symbols in Figure 6.35.

<table>
<thead>
<tr>
<th>Legend</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red line</td>
<td>Isolated overhead line</td>
</tr>
</tbody>
</table>

Figure 6.34 Graphical user interface of the tool for the demonstration of the developed state estimation algorithm
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue line</td>
<td>Low voltage cable</td>
</tr>
<tr>
<td>Yellow line</td>
<td>Cable not in operation</td>
</tr>
<tr>
<td>Red circle with the label PV</td>
<td>Photovoltaic system</td>
</tr>
<tr>
<td>Red filled circle</td>
<td>Local substation</td>
</tr>
</tbody>
</table>
| 1 (85)/71                     | 1: Network node on the primary side of the local substation transformer (in case of a viewing of the low voltage network)  
(85): Network node on the primary side of the local substation transformer (in case of a combined viewing of the medium voltage and low voltage networks)  
71: Network node on the secondary side of the local substation transformer |
Figure 6.35 A low voltage grid of the DSO Vorarlberg Netz in Austria

The specified powers of the loads and the photovoltaic system at respective network nodes are given in the Appendix 7. 24 hour profiles are used for the simulation. These profiles are given in Table 6.3 and the respective active power curves are in the Appendices 3, 4 and 5. A power factor of 0.9 is selected. This value is a good approximation for the reactive power demand of loads in low voltage networks.
Table 6.3 Description of the used profiles in the low voltage network

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load_P_const_0.txt</td>
<td>No load, 96 values all equal to 0</td>
</tr>
<tr>
<td>Load_P_VKW_1.txt</td>
<td>Load profile 1 with values from smart meter 1 of the DSO “Vorarlberg Netz”</td>
</tr>
<tr>
<td>Load_P_VKW_2.txt</td>
<td>Load profile 2 with values from smart meter 1 of the DSO “Vorarlberg Netz”</td>
</tr>
<tr>
<td>Load_P_VKW_3.txt</td>
<td>Load profile 3 with values from smart meter 1 of the DSO “Vorarlberg Netz”</td>
</tr>
<tr>
<td>Load_P_VKW_4.txt</td>
<td>Load profile 4 with values from smart meter 1 of the DSO “Vorarlberg Netz”</td>
</tr>
<tr>
<td>Load_P_VKW_5.txt</td>
<td>Load profile 5 with values from smart meter 1 of the DSO “Vorarlberg Netz”</td>
</tr>
<tr>
<td>Load_P_MySmM.txt</td>
<td>Load profile of a five-person household</td>
</tr>
<tr>
<td>Load_P_PVBu_130613.txt</td>
<td>Good weather generation profile of a 16.5 kW PV system</td>
</tr>
<tr>
<td>Load_P_PVBu_020613.txt</td>
<td>Bad weather generation profile of a 16.5 kW PV system</td>
</tr>
<tr>
<td>Load_P_Schrein.txt</td>
<td>Load profile of a carpentry</td>
</tr>
<tr>
<td>Load_P_const_1.txt</td>
<td>Constant 1W (96 values all equal to 1)</td>
</tr>
</tbody>
</table>

The line data (amongst others resistances, reactances, susceptances) in the positive sequence are given in the Appendix 8.

The data of the transformer at the local substation are given in Table 6.4.

Table 6.4 Data of the transformer at the local substation of the low voltage network

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>12 kV</td>
</tr>
<tr>
<td>Rated apparent power</td>
<td>400 kVA</td>
</tr>
<tr>
<td>Ratio N</td>
<td>11.25 kV/0.42 kV</td>
</tr>
<tr>
<td>Rated short-circuit voltage (u_{kr})</td>
<td>4.25%</td>
</tr>
<tr>
<td>Ohmic voltage drop (u_{Rr})</td>
<td>0.903%</td>
</tr>
</tbody>
</table>

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The accuracies of used measurement systems (smart meters and measurement system at the transformer) are given in Table 6.5 for different measured quantities.

**Table 6.5** Accuracies of used measurement systems when measuring different quantities

<table>
<thead>
<tr>
<th>Measured quantities</th>
<th>Accuracies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage magnitude (smart meter)</td>
<td>±1.0%</td>
</tr>
<tr>
<td>Voltage angle (smart meter)</td>
<td>±1.0%</td>
</tr>
<tr>
<td>Active power (smart meter)</td>
<td>±2.2%</td>
</tr>
<tr>
<td>Reactive power (smart meter)</td>
<td>±2.2%</td>
</tr>
<tr>
<td>Active power (measurement device at the substation)</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Reactive power (measurement device at the substation)</td>
<td>±0.5%</td>
</tr>
</tbody>
</table>

Each solar module of the PV system in the network has the following data:

**Table 6.6** Data of each solar module of the PV system in the network

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum peak power</td>
<td>102 $W_p$ (±5%)</td>
</tr>
<tr>
<td>Number of cells</td>
<td>48</td>
</tr>
<tr>
<td>Voltage (under load)</td>
<td>23.2 V</td>
</tr>
<tr>
<td>Current (under load)</td>
<td>4.40 A</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>4.88 A</td>
</tr>
<tr>
<td>Interconnection allowed till</td>
<td>840 V</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1276 mm x 638 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>5 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>8.5 kg</td>
</tr>
</tbody>
</table>

In these scenarios, the only measurements performed in the network are power measurements (active and reactive power) at network nodes. Noise is added to all input quantities and then the resulting quantities are handed over to the estimation algorithm. For the following considerations, node 21 (almost in the top left corner in Figure 6.35) is selected as the reference node.
The following errors are calculated for evaluating the accuracy of the state estimation algorithm:

\[ Voltage_{angle\_error} = \frac{\delta_{real} - \delta_{estimated}}{360^{\circ}} \times 100\% \quad \text{Equation 6.49} \]

\[ Voltage_{magnitude\_error} = \frac{|V_{real} - |V_{estimated}|}{V_{rated}} \times 100\% \quad \text{Equation 6.50} \]

This error applies to all network nodes and at all discrete time steps.

6.5.4.1 Scenario 1: Accuracy of the state estimation algorithm in case of power measurements at all network nodes

A simulation of the network with power measurements installed at all network nodes and the use of the state estimation algorithm give the curves illustrated in Figure 6.36 and Figure 6.37.

![Active Power at node 21](image)

![Reactive Power at node 21](image)

**Figure 6.36** Powers at node 21 in case of power measurements at all network nodes
In both figures, the magenta curves are from the simulation of the “real world” and the red diamonds show the estimates from the state estimation algorithm. The black curve in Figure 6.36 represents the noisy measurement signal. In Figure 6.37, the black curve displays the approximate voltage value (at node 21) obtained from a load flow calculation after the reconstruction of missing measurements (with the second method).

It can be seen from the figures that the estimates are very close to the real world values for all network quantities and that the errors are very small.

6.5.4.2 Scenario 2: Accuracy of the state estimation algorithm in case of different number of measured nodes

The estimation accuracy in case of different number of measured nodes is examined now. The active and reactive power values are measured only at some selected nodes (100%, 75%, 50%, 25% and 0% of the total number of nodes) and an estimation of the network state is performed using the state estimation algorithm. Both reconstruction methods mentioned in Subsection 6.5.3 are applied and all results are compared at the end.

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6.5.4.2.1 Estimation of node measurements using the 1st method for reconstruction of unmeasured quantities (use of power difference)

As already mentioned in Subsection 6.5.3, this method determines the power difference between the measured power at the transformer feed-in point and the sum of the measured node powers. This power difference is then distributed equally on all unmeasured nodes. Good results can be expected from this method only in the case of a relatively homogeneous network loading.

Assuming that there are no power measurements available at the nodes 2 to 71 (i.e. node 2 to 71 are unmeasured), then the following results are obtained at node 21.

**Figure 6.38** Power at node 21 in case of unmeasured network nodes (2 till 71) and using the 1st reconstruction method (*Note the units on the Y-axis in both cases are MW x 10^3 and MVAr x 10^3 respectively.*)
As it can be seen in Figure 6.38, the reconstruction method gives already a rough approximation of the load flow estimation (black curve). A far better estimation is achieved by means of the Kalman filter (red diamonds). In Figure 6.39, the estimated voltage amplitude (red diamonds) is very near to the actual voltage (magenta curve).

Depending on the number of unmeasured nodes, the estimation errors are of different amplitudes. Table 6.7 shows the obtained estimation errors over all network nodes in case of different numbers of unmeasured nodes.
Table 6.7 Estimation errors in case of different number of unmeasured nodes and using the 1st reconstruction method

<table>
<thead>
<tr>
<th>Measurement coverage [%]</th>
<th>All nodes are measured (100%)</th>
<th>Unmeasured Nodes 11 … 30 (76.5%)</th>
<th>Unmeasured Nodes 11 … 50 (52.9%)</th>
<th>Unmeasured nodes 2 … 61 (29.4%)</th>
<th>Unmeasured nodes 2 … 71 (17.6%)</th>
<th>All nodes are unmeasured (0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average voltage angle error [%]</td>
<td>0.001</td>
<td>0.006</td>
<td>0.001</td>
<td>-0.007</td>
<td>-0.012</td>
<td>Algorithm doesn’t converge</td>
</tr>
<tr>
<td>Average voltage amplitude error [%]</td>
<td>-0.007</td>
<td>0.091</td>
<td>0.050</td>
<td>-0.082</td>
<td>-0.052</td>
<td></td>
</tr>
<tr>
<td>Maximum voltage angle error [%]</td>
<td>0.030</td>
<td>0.184</td>
<td>0.114</td>
<td>0.106</td>
<td>0.098</td>
<td></td>
</tr>
<tr>
<td>Maximum voltage amplitude error [%]</td>
<td>0.203</td>
<td>2.073</td>
<td>1.255</td>
<td>0.595</td>
<td>1.173</td>
<td></td>
</tr>
<tr>
<td>Minimum voltage angle error [%]</td>
<td>-0.019</td>
<td>-0.153</td>
<td>-0.117</td>
<td>-0.166</td>
<td>-0.113</td>
<td></td>
</tr>
<tr>
<td>Minimum voltage amplitude error [%]</td>
<td>-0.200</td>
<td>-1.580</td>
<td>-1.010</td>
<td>-1.145</td>
<td>-1.290</td>
<td></td>
</tr>
</tbody>
</table>
The lowest voltage amplitude error lies at 0.2% when the powers are measured at all network nodes. As illustrated in Figure 6.40, a significant increase of the voltage amplitude error can be observed in case of a measurement coverage of 76.5% (3rd column in Table 6.7). This is due to the unmeasured power infeed of the PV system at node 28 (node with the PV system). Since this power at node 28 is unmeasured, a portion of the determined power difference is assigned to it (node 28). As illustrated in Figure 6.41, this unmeasured power infeed of the PV system also leads to high estimation errors at the nodes 2 till 28 which are all located in the same network branch going from the transformer (see Figure 6.35).

The algorithm diverges in the case of a high power difference. In this scenario, this situation occurs when no power measurements are performed in the network (7th column in Table 6.7).

![Feed-in power comparison](image)

**Figure 6.40** Estimation error in case of different number of measured nodes and using the 1st reconstruction method
6.5.4.2.2 Estimation of node measurements using the 2\textsuperscript{nd} method for reconstruction of unmeasured quantities (use of generation and load profiles)

As already mentioned in Subsection 6.5.3, the reconstruction of missing measurements is done in this method by using profiles (generation and load profiles) as replacement values at the unmeasured nodes. These profiles can be obtained from historical data or from a forecast. Therefore, better results than with the first method can be expected.

Assuming that there are no power measurements available at the nodes 2 to 71 (i.e. node 2 to 71 are unmeasured), then the following results are obtained at node 21. The profile in Figure 121 (in Appendix 4) is used as load profile. It is normalized to a two-person household.
Figure 6.42 Powers at node 21 in case of unmeasured network nodes 2 to 71 and using the 2\textsuperscript{nd} reconstruction method (Note the units on the Y-axis in both cases are MW x 10\textsuperscript{-3} and MVAr x 10\textsuperscript{-3} respectively.).

Figure 6.43 Complex voltage at node 21 in case of unmeasured network nodes 2 to 71 and using the 2\textsuperscript{nd} reconstruction method

Figure 6.42 shows the scaled load profile (black curve). The estimate (red diamonds) is very close to the real world values (curve in magenta).
The estimated node voltage amplitude in Figure 6.43 is up to 2% close to the actual node voltage amplitude (synthetic world value).

Table 6.8 gives the obtained estimation errors in case of different number of unmeasured nodes.
Table 6.8 Estimation errors in case of different number of unmeasured nodes and using the 2\textsuperscript{nd} reconstruction method

<table>
<thead>
<tr>
<th>Measurement coverage [%]</th>
<th>All nodes are measured</th>
<th>Unmeasured Nodes 11 … 30 (76.5%)</th>
<th>Unmeasured Nodes 11 … 50 (52.9%)</th>
<th>Unmeasured nodes 2 … 61 (29.4%)</th>
<th>Unmeasured nodes 2 … 71 (17.6%)</th>
<th>All nodes are unmeasured (0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average voltage angle error [%]</td>
<td>0.001</td>
<td>-0.006</td>
<td>-0.012</td>
<td>-0.019</td>
<td>-0.022</td>
<td>-0.021</td>
</tr>
<tr>
<td>Average voltage amplitude error [%]</td>
<td>-0.007</td>
<td>-0.170</td>
<td>-0.234</td>
<td>-0.320</td>
<td>-0.348</td>
<td>-0.330</td>
</tr>
<tr>
<td>Maximum voltage angle error [%]</td>
<td>0.030</td>
<td>0.038</td>
<td>0.030</td>
<td>0.037</td>
<td>0.036</td>
<td>0.040</td>
</tr>
<tr>
<td>Maximum voltage amplitude error [%]</td>
<td>0.203</td>
<td>0.095</td>
<td>0.053</td>
<td>0.088</td>
<td>0.013</td>
<td>0.058</td>
</tr>
<tr>
<td>Minimum voltage angle error [%]</td>
<td>-0.019</td>
<td>-0.032</td>
<td>-0.072</td>
<td>-0.089</td>
<td>-0.104</td>
<td>-0.105</td>
</tr>
<tr>
<td>Minimum voltage amplitude error [%]</td>
<td>-0.200</td>
<td>-1.183</td>
<td>-1.313</td>
<td>-1.965</td>
<td>-2.043</td>
<td>-2.050</td>
</tr>
</tbody>
</table>
Figure 6.44 shows that the voltage magnitude and voltage angle errors decrease when the number of measured nodes increases. For the selected network, the voltage magnitude error reaches a highest value lying slightly above 2% for almost no node measurements in the network.

![Graph showing voltage errors vs. number of measured nodes]

Figure 6.44 Estimation error in case of different number of measured nodes and using the 2nd reconstruction method (translation in Appendix 13)

Therefore, it can be deduced that this method provides a good network state estimation also in case of very little number of measurements in the network.

6.5.4.2.3 Comparison of both reconstruction methods

Both methods yield comparable results with this reference network. A state estimation using the 1st reconstruction method has the following advantages and disadvantages.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>The node powers may not be known</td>
<td>A high inaccuracy of network quantities is obtained in case of a high power difference. This can lead to a divergence</td>
</tr>
</tbody>
</table>

Table 6.9 Advantages and disadvantages of the state estimation using the 1st reconstruction method
of the algorithm.

<table>
<thead>
<tr>
<th>Generation and load profiles are not necessary</th>
</tr>
</thead>
</table>

A state estimation using the 2\textsuperscript{nd} reconstruction method has the following advantages and disadvantages.

**Table 6.10** Advantages and disadvantages of the state estimation using the 2nd reconstruction method

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>It works also in cases of little number of measurements</td>
<td>Adapted generation and load profiles are necessary</td>
</tr>
</tbody>
</table>

### 6.5.4.3 Scenario 3: Accuracy of the state estimation results in case of different measurement sampling intervals

In this subsection, the behaviour of the state estimation algorithm at different power measurement sampling times is investigated. Minute, averaged minute, averaged ¼-h and averaged ¼-h power measurement values over several days are considered. The 2\textsuperscript{nd} reconstruction method and the previous low voltage network are used for the investigation. In addition, all nodes are measured.

#### 6.5.4.3.1 Minute power measurement values

For this investigation, the recorded power measurements given in Appendix 7 are used as input of the state estimation tool. These records are from smart meters installed in the network of the DSO “Vorarlberg Netz” and were done over the weekdays (Monday to Friday). Since the power measurement values were sampled every minute, there are in total 1440 values per measurement type per day. Each node in the network is assigned one of these records.
Figure 6.45 Powers at node 21 over a day when using minute sampled power measurement values

Figure 6.46 Complex voltage at node 21 over a day when using minute sampled power measurement values

Figure 6.47 and Figure 6.48 show respectively the selected sections (red frames) from Figure 6.45 and Figure 6.46 at the sampling time from 681 to 776 (this represents the time period from 11:20 to 13:00).
Figure 6.47 Powers at node 21 over a day at the sampling times from 681 till 776 (from Figure 6.45)

Figure 6.48 Complex voltage at node 21 over a day at the sampling times from 681 till 776 (from Figure 6.46)
6.5.4.3.2 Averaged minute power measurement values

Here, the averaged minute power measurement values are used as input of the state estimation tool. For this purpose, the power measurement values made every second are averaged over one minute. There are in total 1440 values per measurement type per day.

Figure 6.49 Powers at node 21 over a day when using averaged minute power measurement values
Figure 6.50 Complex voltage at node 21 over a day when using averaged minute power measurement values

Figure 6.51 Powers at node 21 over a day at the sampling times from 681 to 776 (from Figure 6.49)
Figure 6.52 Complex voltage at node 21 over a day at the sampling times from 681 to 776 (from Figure 6.50)

6.5.4.3.3 Averaged ¼-h measurement values

Here, the averaged power measurement values over 15 minutes are used as input of the state estimation tool. For this purpose, the sampled minute power measurements from the profiles in the Appendix 7 are averaged over 15 minutes. New profiles with in total 96 values per day are generated. Each node in the network is assigned one of these profiles.
Figure 6.53 Powers at node 21 over a day when using the averaged ¼-h power measurement values

Figure 6.54 Complex voltage at node 21 over a day when using the averaged ¼-h power measurement values
6.5.4.3.4 Averaged ¼-h power measurement values over several days

Here, the averaged ¼-h power measurement values are averaged over several working days. The new profiles are used as input of the state estimation tool. These new profiles are more smoothed than all others.

Figure 6.55 Powers at node 21 over a day when using the averaged ¼-h power measurement values over several days
Figure 6.56 Complex voltage at node 21 over a day when using the averaged ¼-h power measurement values over several days

6.5.4.3.5 Comparison of the measurement sampling interval variants

Table 6.11 shows a comparison of the estimation errors when using the four examined sampling interval variants. The error computation in the table below is done over all network nodes.

Table 6.11 Estimation errors in case of different sampling interval variants and using the 2nd reconstruction method

<table>
<thead>
<tr>
<th></th>
<th>Minute sampled power</th>
<th>Averaged minute sampled powers</th>
<th>Averaged ¼-h sampled powers</th>
<th>Averaged ¼-h sampled powers over several days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average voltage angle error [%]</td>
<td>0.000</td>
<td>-0.000</td>
<td>-0.000</td>
<td>-0.001</td>
</tr>
<tr>
<td>Average voltage amplitude error [%]</td>
<td>-0.000</td>
<td>0.001</td>
<td>-0.003</td>
<td>0.002</td>
</tr>
</tbody>
</table>
The developed state estimation algorithm is relatively insensitive to power variations and jumps in the “synthetic real world”.

**Figure 6.57** displays graphically the highest obtained estimation errors (values from Table 6.11).

![Image](image_url)

**Figure 6.57** Estimation errors in case of different sampling interval variants and using the 2nd reconstruction method (translation in **Appendix 13**)

<table>
<thead>
<tr>
<th>Maximum voltage angle error [%]</th>
<th>0.034</th>
<th>0.026</th>
<th>0.020</th>
<th>0.016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum voltage amplitude error [%]</td>
<td>0.305</td>
<td>0.260</td>
<td>0.140</td>
<td>0.155</td>
</tr>
<tr>
<td>Minimum voltage angle error [%]</td>
<td>-0.024</td>
<td>0.023</td>
<td>-0.017</td>
<td>-0.022</td>
</tr>
<tr>
<td>Minimum voltage amplitude error [%]</td>
<td>-0.300</td>
<td>-0.263</td>
<td>-0.250</td>
<td>-0.190</td>
</tr>
</tbody>
</table>

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6.5.4.4 Scenario 4: Detection and correction of measurement outliers

In this subsection, the detection and correction of outliers by the state estimation algorithm are demonstrated. For this, a random value between -20 to 20 kW (resp. kVAr) is added at the sampling time 79 to the active (resp. reactive) power measurement performed at the node 21. The same low voltage network is used here.

Without performing any detection and correction of measurement outliers, the estimated value follows the measured value. As a result, an error is generated and then propagated in the next time step (red diamonds from the sampling time 79 to 85 in Figure 6.58).

Figure 6.58 Measurement outlier during the state estimation by deactivated error detection and correction algorithm

When using the error detection and correction algorithm, the estimates are close to the actual values (Figure 6.59).
Figure 6.59 Measurement outliers during the state estimation by activated error detection and correction algorithm

6.6 Other tools

6.6.1 Generation and load forecast

Due to the large number of intermittent generation plants (mainly wind turbines and photovoltaic systems) in distribution networks, a generation forecast of these plants is absolutely necessary for the planning of the network operation. A load forecast is also important. A network state prediction can be performed with the forecasted generation and consumption values to determine whether any problems could occur during the operational phase.

The input data for a generation and load forecast are the weather forecast data in the respective distribution area. The weather forecast data are supplied by meteorological services and these include among others data such as wind speed, wind direction, temperature, humidity and others. From these data and additional data (e.g. generation and consumption values from the past, plant and load data, installation location of plants in the network area), the generations of the intermittent plants and the load consumptions are determined in the control center. For the determination, methods such as neural networks can be used successfully. The resulting forecast quality highly
depends on the forecast errors in the forecasted weather information and the forecast accuracy of the method used for forecasting plant generations and load consumptions.

### 6.6.2 Grid state forecast

During the operational planning phase, a forecast of the expected network state during the operational phase can be performed by using this tool. Thereby it is possible in advance of the operation phase to forecast the network situation (load flow, voltage profile) and to identify any eventual problems (e.g. congestions and voltage limit violations). As soon as eventual problems are identified, countermeasures for mitigation or avoidance can be developed. If some of the forecasted problems are about to occur during the operational phase, then the respective prepared countermeasures can immediately be deployed.

The network topology, the planned network events (e.g. network switchings, maintenance, construction, repair measures), the time horizon, the planned and forecasted generation and consumption schedules (see Subsection 3.2.2) are given as input to the tool. Using this input, a load flow calculation is carried out over the entire given time horizon. The results from the load flow calculation (voltage profile, voltage angle, power flow in the grid) are analyzed to identify any potential problems. In case of possible problems, preventive measures are generated using specialized tools (e.g. tool for voltage management, load flow management, topology management). Once operational recommendations (preventive measures) from these tools are available, a network state prediction is performed again taking into account the operational recommendations. This is done until all problems are mitigated or fully avoided.

### 6.6.3 Topology management

Topology change is one of the network-based measures that can be used by a network operator for solving problems encountered in its network. The aim is to influence the power flows and hence influence the voltage profile by changing the network switching state. However, some important aspects as the short-circuit power of the network, the reaction of protection equipment, the adjustment of earth-fault suppression coils (if
available) and others must be considered before performing changes of the network switching state.

In case of problems in the network and taking into consideration the aspects mentioned above, the topology management tool should generate optimal, efficient and reliable switching options (operational recommendations) for solving the occurred problems. These operational recommendations are then presented to the control center staff who will decide to entirely execute or to adjust the operational recommendations before execution or to reject the actions listed in the operational recommendations.

### 6.7 Summary

In this chapter, four approaches for the optimal and efficient management of Smart Grids were described and, respective tools were developed and demonstrated.

The first tool enables a power loss reduction, an improvement of voltage profile and a reduction of the reactive power flow in networks by adjusting the reactive power supplies. Based on the network topology and the reactive power consumption at each node, the tool computes the optimal reactive power level of each available generator. The demonstration of the tool on networks led to improvements of the network situation and the mentioned advantages (in Section 6.2) could be observed.

The second tool is a causer pays generation and load management tool for congestion and load flow management. It computes the active power contribution of each generator to the active power flow on each branch in the network based on the actual network state obtained from a load flow calculation or a network state estimation. In the case of congestion or an overload, the appropriate generators to efficiently solve the problem are selected using the newly developed approach which was presented. At the end, the required active power adjustments of the selected generators are computed by performing a sensitivity analysis. It is important to mention that the first tool is integrated in the actual tool to achieve much better results. The demonstration of the tool gave excellent results and the comparison of different congestion strategies showed the benefits (technical, economical, social) of the new approach.

The third tool is a topology-based generation and load adjustment tool for voltage management. Based on the network topology and the actual network state obtained from a load flow calculation or a network state estimation, the tool performs in case of
voltage limit violations in the network the selection of appropriate generators for efficiently solving the problem and computes the required active power adjustments of the selected generators using the developed approach. It is important to mention that the first tool is also integrated in the actual tool to achieve much better results. The demonstration of the tool yielded excellent results.

The last tool is used for network state estimation in distribution grids by lack of measurements. Using the newly developed computation model and a Kalman filter, the network state can be well estimated with very minimal errors. The demonstration of the tool yielded excellent and very promising results.

In addition to these four tools, three other important tools for the management of Smart Grids were briefly described. These were tools for generation and load forecasting, network state prediction and topology management.
Chapter 7 “HSE 2020” Case Study - Implementation of the Network Training System at the DSO RMN Control Center in Darmstadt

7.1 Introduction

The results achieved in the previous chapters (developed network training system and tools) should now be used in practice. The practical use is done together with the local DSO RMN in Darmstadt within the project “HSE 2020”.

In Section 7.2, the DSO RMN is presented and the goals of the project “HSE 2020” are given. The modelling of the future HSE distribution network by year 2020 in the network training system for the training of the DSO’s control center staff is described and the resulting network model is presented in Section 7.3. In Section 7.4, the developed Smart Grid training scenarios are presented. The installation of the network training system at the control center of the DSO RMN is described in Section 7.5. The training concept established together with the DSO, the preparation of the training, the training process and the feedback (from the control center staff and the DSO) after the first training rounds are given in Section 7.6. The further uses of the training system are presented in Section 7.7.

7.2 Presentation of the Distribution System Operator Rhein Main Neckar (DSO RMN) and goals of the project “HSE 2020”

The HSE AG (HEAG Südhessische Energie AG) is a large utility company in the German federal state Hesse [79] and has a geographically large extensive distribution network. Figure 7.1 shows the entire supply area in detail and within the Federal Republic of Germany (location and area).
After the splitting of the company as a result of the liberalization of the energy market, the DSO RMN (Distribution System Operator Rhein Main Neckar) emerged as a network operator. The DSO RMN is responsible for the operation, servicing, expansion, extension, maintenance and repair of the HSE distribution network. Currently, the distribution system consists of the medium (20 kV) and low voltage (0.4 kV) levels. It has about 43 substation transformers (110/20 kV transformers), about 4000 local substations and a peak load of 750 MW. Nowadays many renewable energy plants of different technologies (e.g. photovoltaic systems, wind turbines, biogas plants and hydroelectric power plants) feed in the network and the connection of many more plants is expected in the future.

The described changes in Chapter 3 are already taking place in the HSE distribution network and these lead to many new challenges and requirements. Apart from the measures for upgrading and preparing the network, it is absolutely essential to prepare...
the control center staff through training for the future network management (mentioned in Chapter 3). Therefore, the HSE and the DSO RMN have initiated in cooperation with the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da) the project “HSE 2020”. The aims of the project were the analysis, design, implementation and commissioning of a network training platform to be used for the training of the control center staff. A modelling of the future HSE distribution network by year 2020 should be done in the network training system. This allows the control center staff to train directly on its own network. Another aim of the project was the development of training scenarios.

7.3 Preparation of the training network

A modelling of the future HSE network by year 2020 was performed for the training of the control center staff. Given the size of the real network and the associated modelling effort, the targeted meaningfulness of the training and the limited duration of the project, the project partners decided that a detailed modelling of the entire HSE network is not necessary. Thereupon, the DSO RMN selected a part of the network in which the performing of all defined scenarios (will be presented in Section 7.4) for the staff training would be accurate and reasonably possible. The selected part was modelled true to detail and the remaining part was aggregated.

7.3.1 Truly detailed modelled part network

The “truly detailed modelling of the part network” means that all real network and component data (i.e. line data, protection settings, switch positions, generator data, load data and others) are entered into the network training system to build the data model of the part network. The truly detailed modelled part network of the HSE network is a medium voltage network (20 kV) composed of 5 110/20 kV substation transformers (2 in station 1, 2 in station 3 and 1 in station 8), 8 substations and about 170 local substations. Figure 7.2 shows the overview screen of the part network.
Figure 7.2 Overview display of the truly modelled part network

Figure 7.3 to Figure 7.10 show magnified areas from Figure 7.2.
Figure 7.3 Overview display of the truly modelled part network (1\textsuperscript{st} section from left up to left down)

Figure 7.4 Overview display of the truly modelled part network (2\textsuperscript{nd} section from left up to left down)
**Figure 7.5** Overview display of the truly modelled part network (3\textsuperscript{rd} section from left up to left down)

**Figure 7.6** Overview display of the truly modelled part network (4\textsuperscript{th} section from left up to left down)
Figure 7.7 Overview display of the truly modelled part network (1st section from right up to right down)

Figure 7.8 Overview display of the truly modelled part network (2nd section from right up to right down)
Based on the current state of the network, the modelling of the part network was carried out under consideration of currently ongoing and of planned conversions and expansions until the year 2020. The planned connections of generators (photovoltaic systems, wind turbines, CHP), loads, reactive power compensation units and other equipment were taken into consideration.

Given the important role of energy storages in Smart Grids, a few of them have been integrated into the part network although they are yet not present in the real network.
This allows the control center staff to train in advance the use of energy storage in the network operation management, to explore their possibilities and potential.

To limit the modelling effort, the low voltage networks behind the local substations were not modelled in detail. All component types (including photovoltaic systems, wind turbines, load and energy storage systems) in a low voltage network were aggregated each into a single component. These aggregated components were then connected to the 20 kV busbar in the local substation. **Figure 7.11** illustrates the structure of a local substation with aggregated components.

![Virtual power plant](image)

**Figure 7.11** Structure of a local substation with aggregated components

**Figure 7.12** shows a modelling example of the low voltage network behind the local substation “ST049”. Only the aggregated photovoltaic system and the load are to the 20 kV busbar in the local substation “ST049”.

![Local substation “ST049” with aggregated photovoltaic system and aggregated load](image)

**Figure 7.12** Local substation “ST049” with aggregated photovoltaic system and aggregated load

The 20 kV part network is supplied by the 5 110/20 kV substation transformers. These
transformers are connected on their primary sides to a 110 kV substation (Figure 7.13). The following components are also connected to this substation:

- The feed-in feeder (“Verbund”) of the TSO is connected to it.
- A wind farm with a maximum power of 140 MW. Although this wind farm is installed in reality in the North Sea, it is however connected to this station. This decision is based on the building of a balancing group. As a result, the performing of scenarios in the context of energy management is for example possible (as mentioned in Subsection 3.3, this task is actually not under the responsibility of network operators).
- A solar power plant with a peak power of about 20 MW.
- A peak load gas power plant with a maximum power of 100 MW.

The aggregated part network is also connected to this substation and is described in the next subsection.

![Figure 7.13 110 kV transfer substation](image)

Overview, plant and equipment displays were realized for the visualization. Overview displays provide overview information (e.g. global network overview, overview of load groups). Station displays contain station-related information (substation, local substation) and component displays show equipment information (states, measurement values, target values). **Figure 7.14 to Figure 7.16** illustrate examples of display types.
Figure 7.14 Overview display
Figure 7.15 Station display

Figure 7.16 Equipment display
7.3.2 Aggregated part network

The aggregated part network is connected to the 110 kV transfer substation and consists of the remaining substation transformers supplying their respective network areas. Here however, the network behind each substation transformer was not modelled in detail. An aggregation of all planned and existing component types in each respective network into a single component was performed. The aggregated components were then connected to the 20 kV busbar on the secondary side of their respective substation transformers. **Figure 7.17** shows the overview display with the aggregated part networks.

![Figure 7.17 Overview display of the aggregated part networks](image)

**Figure 7.17** Overview display of the aggregated part networks

**Figure 7.18** shows the structure of an aggregated 20 kV network group.
Figure 7.18 Structure of an aggregated 20 kV network group, e.g. the station “STZ03”
(translations in Appendix 13)

Figure 7.19 shows the station “STZ03” with the connected aggregated components.
The aggregated part network plays a role in network training so far that it makes the reaching of the peak load of the entire real network possible, and enables the performing of specific network tasks such as ancillary services support through the Smart Grid in case of frequency and voltage problems in the transmission network, and also market-based tasks such as energy management (nowadays not under the responsibility of network operators).

Overview, plant and component displays were realized for visualization purposes. A change from one display to others is possible via selection buttons.

### 7.4 Training scenarios

These enable the control center staff to train the aforementioned new problems in distribution networks. For the training of the control center staff of the DSO RMN, several training scenarios were initially developed and working out. Seven of these scenarios will be described in more detail here. These are:

- Voltage problems in the medium voltage supply area with high infeeds from renewable energy plants
- Load flow problems in the medium voltage supply area with high infeeds from wind farms
• Voltage spreads in the low voltage network
• Detection of a masked overload on a network line track
• Reaction to voltage problems in the upstream network
• Reaction to frequency problems in the interconnected system
• Active energy management in the Smart Grid - Compensation of spontaneous energy deficits

The individual training scenarios are described in the following subsections.

7.4.1 Voltage problems in the medium voltage supply area by high infeeds from renewable energy plants

It is a cloudless summer day at midday. The voltages in a supply area with high infeeds from renewable energy plants increase and lead to voltage upper limit violations at many local network distribution transformers (MV/LV transformers). The local automatics are at their limits. Respective messages are received in the control center. Two possibilities are given to get the voltage back in the normal range:

• Connection of a reactive power compensation unit to consume inductive reactive power
• Charging of a battery storage

Both possibilities lower the voltage. The first possibility increases the power losses due to the higher amount of current flow in the network. The second possibility may be more effective because of the R/X ratio and causes lower losses. However, both measures are limited in their spatial effect.

Another possibility is a tap position change of the HV/MV transformer. However, this measure affects the entire supply area and could be dangerous because a tap position change of the supplying HV/MV transformer could for instance cause a voltage drop in network areas with high load consumptions and no infeeds.

In this medium voltage supply area, there is also the possibility of meshing of open operated rings. This measure can also lower the voltage level; however, the risk of a higher number of consumer disconnections is given in the case of a network fault. One could consider a ring operation whereby the ring is closed by HV HRC fuses and disconnectors.
The decisions and their consequences are to be trained, whereby the solution depends on the incoming messages from the network and the available components in the network.

### 7.4.2 Load flow problems in the medium voltage supply area by high infeeds from wind farms

A wind farm repowered to 30 MW is connected at a network point far away from the substation transformer and is feeding power into the grid. The wind farm is connected via three feeders to the network.

One feeder is not available for a long time due to conversion measures in a substation, see Figure 7.20. There is a new request for an urgent shutdown of a line. Based on the weather forecast results (very slow wind), the switching request is initially approved and the line (in the middle of Figure 7.20) is isolated and grounded. Following this action, the line is displayed in yellow-green in the control system.

The following scenario is triggered: Contrary to the weather forecast, sudden growing and stronger wind appears on the day. The power generation of the wind farm grows accordingly. The power in the last feeder leads to a critical overload situation on the line. First, the 80% limit is exceeded, and a warning (red-marked “W”) is displayed. The power from the wind farm continues to increase. There are no additional lines or battery storage units available nearby. As long as the work of the last approved switching request can still be cancelled, this solution is to be preferred. If not, the power infeed of the wind farm can be reduced.

![Figure 7.20 Load flow problem in the MV network by high infeed from a wind farm, red bar means open switch-disconnector, white line means line is without voltage, yellow-green line means grounded line](image)

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7.4.3 Voltage spreads in the low voltage network

In a supply area of a local network transformer, there are several large private photovoltaic systems that are connected to 400 V. The station feeds several residential areas in a rural vast area. The load condition is quite high. Clouds cause shading of one area, while the remaining part area is exposed to the sun. A voltage increase occurs in the sunny network area due to the surplus of production while a voltage drop is registered in the line tracks with high load consumption. Decreasing the tap position of the transformer at the local substation would bring the voltage of the sunny part of the network back into the permissible limits. However, the voltage in the shaded part of the network would be brought through this action below the allowable limit. Due to this local problem which cannot be solved without power adjustments in the network, a message is sent to the control center. A manual switching of a remote controlled battery unit can solve the problem. If the battery storage unit is installed in the network part with the highest voltage, then a charging of the battery leads to a voltage drop. If the battery storage is rather installed in the network part with the lowest voltage, then a discharging of the battery leads to a voltage rise. The voltage problem in the other network part can be solved through adjustments of the tap position of the local network transformer. Since this problem could appear in future in many local networks almost simultaneously, a local automated control of both the storages and the target voltage of the variable local network transformer by means of a Micro Grid Manager (MGM) is to be achieved. However for didactic purposes, the control can also be triggered manually in a training session for staff awareness.

7.4.4 Detection of a masked overload on a network line track

In a supply area of a transformer (see Figure 7.20), there are a number of larger distributed PV plants and industrial consumers, mixed with household consumers. Scenarios can be set up where a simultaneous increase of load consumptions and PV infeeds causes a measured current at the beginning of the line track (near the transformer) which is lesser than the rated current, but a significantly higher current masked by the PV infeeds flows in far distance network sections of the line track. Such a case can only be detected when monitoring current flows in the distribution network.
After detection, the problem could be solved by, for example topology switchings or adjustments of infeeds and loads.

7.4.5 Reaction to voltage problems in the upstream network

The upstream network operator suffers voltage problems (e.g. undervoltage). The instruction to reduce the power consumption at the connection point between the upstream network and the distribution network is sent to the control center of the DSO. The control center staff now has the following options:

- Shutdown of an interruptible load group for power reduction in the distribution network.
- Start up of a power plant (i.e. biogas, combined heat) present in the network.
- Sending a signal for power reduction by activating a virtual power plant in the form of decentralized small producers.

The options are selected depending on the situation and executed by the control center staff.

7.4.6 Reaction to frequency problems in the interconnected system

There is an underfrequency in the network. Conventionally, a staggered and frequency-controlled load shedding is performed in distribution networks as soon as the frequency gets below 49 Hz to restore the frequency stability. These relays can also be used in case of already smaller frequency deviations to switch distributed battery storages in the network within a few 100 ms to full output power. These battery storages can be qualified in their primary control capability and thus provide ancillary services for frequency stability.

7.4.7 Active energy management in the Smart Grid - Compensation of spontaneous energy deficits

Although this task is nowadays not under the responsibility of network operators, it can be performed excellently with the network training system.
A forecast deviation occurs in the entire Smart Grid due to an unexpected weather change. As a consequence, a production deficit for the next four quarters of an hour will occur. This raises the question of which of the possible measures could be applied to balance the deficit. The cost for using balancing energy would be high. Possible measures are the use of internal storage systems, the use of gas turbines, intra-day trading, a load shedding or the activation of tariff signals for a demand-side management. The decision depends on the availability of units and on goals such as cost minimization, CO₂ emissions minimization. This is a complex decision that should be supported by a software assistant system in the control system. This system generates a list of suggestions which can be partially or fully executed.

7.5 Installation of the network training system at the DSO RMN

Two computer systems (1 desktop and 1 laptop) were purchased and made available for the training in the control center by the DSO RMN. The installation and configuration of all necessary softwares for the network training system (RESY-PMC®, RESY-NES®) were carried out on both computers. The project folder with information about the modelled network (including templates, data model, displays) and the new modules of the network simulator (modules which were generated in the network simulator during the extension of the network training system with new functions and new models) were copied from the development computer to both systems. At the end other necessary settings, adjustments and configurations were needed to get the systems running. Both systems were officially handed over to the DSO RMN and these are already being used for training the control center staff in the control center.

7.6 Training

7.6.1 Training concept

A training concept was established together with the DSO RMN. This stipulated that only three members of the control center staff should go through the prepared training program (will be described in Subsection 7.6.2) and should be trained by the academic
staff of the Darmstadt University of Applied Sciences (Hochschule Darmstadt, h_da). At the end of the training, these members would serve as training coordinators at the DSO control center and should take over the training of the other control center staff members.

The particularity in the selection of these three members is that they were all younger staff members. In the survey about the people interested in the new training, older staff members reacted restrained according to the motto “Until now everything has always worked well, why a new training?”. The younger were rather more interested and motivated. From this experience, the DSO established the training concept according to which, three younger staff members should be initially trained. Then these should train the other younger staff members. The enthusiasm and joy of the younger staff members about the new learned might lead to a conversation with the older. Thereby the curiosity and motivation of the older staff members might be awakened, resulting to their participation to the training.

A training on the network training system can be performed either in group (at least 1 person and the training coordinator) or individually (one person without a training coordinator). A group training requires a coordinator and at least one person. The training coordinator manages and coordinates the entire training (explanations, answers to questions, starting of scenarios, setting of faults). Each staff member must go at least once through this training. If this training is completed, the staff member is allowed to perform individual training. In an individual training, a staff member can train alone at the network training system. It can train with stored scenarios and tasks. It can also create new scenarios, experiment with these, share and discuss its findings with colleagues.

### 7.6.2 Training preparation

A training manual (over 100 pages) was conceived. This training manual consists of two main sections: theory and practice.
The theory section serves the theoretical training and familiarization of the control center staff. Hereby, the focus is on the building of a solid base ahead of the practical training. The control center staff gets:

- a refreshing of the basics of power grids. The focus is on AC technology, substations, grid structures, neutral point treatment, protection devices and current issues.
- an overview of the energy revolution and Smart Grids. Among the points are the definitions and meanings of “energy revolution” and “Smart Grids”, their possible implementation and operation. The Smart Grid components are reviewed, the changes in the network operation and the ancillary services are addressed.
- an introduction to the network training system. Thereby some basic information on the network training system, the components and their operation (on the workstation and over the trainer functionality) are introduced and more points are discussed (e.g. starting and stopping the system and the architecture of the system).
- an introduction to the future power network of the DSO RMN. The modelled network is presented; the network displays, the operation, the alerting and some other points are discussed.

The theoretical training is followed by the practical training. During the practical training, the control center staff exercises at the network training system with the prepared training scenarios. In the training part of the training manual, the following points were prepared for the training:

- Scenarios for training the conventional network operation. This includes exercises such as busbars and transformers interchange, short circuit and earth fault localization, maintenance work with switching orders and switching conversation. One may ask: “Why is a training of the conventional network operation in the Smart Grid era still important?” The conventional network operation represents the basis of network operation and is a prerequisite for the secure, reliable, safe and efficient operation of Smart Grids. The operation of Smart Grids highly depends on it. For example, a busbars interchange performed improperly can cause a network fault, which in turn interfere the operation of the Smart Grid.
Scenarios for the training of Smart Grids. This includes scenarios described in Section 7.4 and which are relevant to the operation of a Smart Grid.

7.6.3 Feedback from the control center staff

After the first training sessions, there were feedbacks from the DSO RMN board and the control center staff. The DSO RMN board considers to have reached its goal with the completion and use of the network training system, namely a tool for the efficient preparation and training of its control center staff for the future network operation. The DSO RMN is the opinion that the network training system exceeds its expectations. The control center staff is very satisfied with the network training system and sees it as a powerful tool with great potential. The control center staff could already try many situations described theoretically in publications and scientific articles with the network training system, analyze the results and discuss these with colleagues, gain new valuable knowledge and insights. The control center staff wished also some improvements, modifications and adaptations to make the training more optimal and efficient. These were taken, processed, integrated into the network training system and delivered. The same applies for practical and operational procedures that cannot be found yet in the literature.

7.7 Further uses of the training system

During the project, a number of papers were published [81, 82, 83, 84, 85, 86] to report on the project, the ideas and the new experience. There was always a positive response. According to information from the DSO RMN, there were several requests from other network operators to exercise with the network training system. This message shows that many network operators are aware of the future problems and challenges, and are searching for adequate tools for training their control center staffs.

In addition for training the control center staff in the control center, the laptop (mentioned in Section 7.5) is also to be used for both internal and external presentations and demonstrations at meetings, conferences and workshops. This allows the DSO to
support his statements through meaningful examples and scenarios with the real-time simulation, whereby the audience's attention is gained even more effectively. The DSO is even more convincing. The following 2 examples support this argument.

First: With the growing number of renewable energy plants, some vulnerable network points require a network reinforcement through the construction of new lines and tracks. The network operators often face resistance from citizens' initiatives, which do not want any new lines and tracks. With means of such a real-time simulation, the respective network operators can use scenarios to present the occurring problems in the network, discuss the dangers and consequences for the energy supply with the citizens, and finally present the need of countermeasures with the resulting improvements and benefits. According to experience, the resistance from citizens are often based on incorrect information, false opinions and an understanding which might not be correct.

Second: As mentioned in Chapter 2, the activities of network operators are controlled and regulated by administrative regulations. In recent years, it could often be observed that adopted laws were more politically than technically driven and were not compatible with the reality of the network operation. In some cases, the network operation was made even more difficult. With a real-time simulation, system operators can demonstrate concrete problems and, so justify and force an adaptation or improvement of laws.

7.8 Summary

The focus in this chapter was on the practical use of the implemented network training system and tools for the training of the control center staff of the DSO RMN in Darmstadt. At first the DSO RMN, its network area and its distribution network were presented. The initiate project entitled “HSE 2020” was described. The aims of the project were the analysis, design, implementation and commissioning of a network training platform to be used for the training of the control center staff. A modelling of the future HSE distribution network by year 2020 should be carried out in the network training system. Due to the size of the real network and the associated modelling effort, the targeted meaningfulness of the training and the limited duration of the project, it was
decided together with the project partners that a detailed modelling of the entire HSE network is not necessary. The DSO RMN selected a part of the network to truly model in detail and the rest of the network was aggregated. Under consideration of the information received from the DSO (such as future plant connections, network expansions, conversions), the network modelling was been successfully carried out and the network simulation was successfully achieved. Overview, plant and equipment displays were realized for the visualization on the workstation.

Training scenarios were developed and elaborated for the training. These address the mentioned new problems in distribution networks (in Chapter 2) and further.

A training concept was also elaborated together with the DSO. This specifies the organization of the training process of its control center staff. In addition, a training manual was conceived. It is composed of two main sections: theory and practice. The theory section serves the theoretical training and familiarization of the control center staff. Hereby, the focus is on the building of a solid base ahead of the practical training. The practice section consists of training scenarios. After the first training sessions, there were positive feedbacks from the DSO RMN and its control center staff. The control center staff also made some improvement, change and adjustment wishes which would make the training more optimal and efficient.

Apart from using the network training system for training the control center staff, it can be used both for internal and external presentations and demonstrations at meetings, conferences and workshops.
Chapter 8  Conclusion and Future Work

8.1  Conclusion

The main goal of this thesis is to analyze the design and operation of future grid structures (Smart Grids) which would allow the infeed of a mass of distributed renewable energy plants. Especially the DSOs have to deal with new types of complex operations and decisions that are close to TSO operations or even more complex. Obviously these tasks should be supported by software tools. Tools are needed to handle with the lack of online data, to estimate the network state, to identify the problem cause and finally to compute the right values and measures to mitigate the problems. To increase skills and professionalism of the control center staff for an efficient grid operation, the problems and solutions should be trained in advance in a risk-free manner using a dynamic simulation system. In this thesis, a set of tools for operating future grids have been designed. After designing the algorithms, all tools have been implemented and tested on several DSO grids. A training simulation system has been extended and a pilot training was successfully performed at the DSO RMN in Darmstadt.

As a conclusion, a final look at the general problem, the solutions achieved and the advantages to work with: Whereas in the past distribution networks (medium and low voltage networks) were largely planned, built and operated as “passive networks”, major changes have occurred in recent decades through the massive installation of distributed renewable energy plants. These networks are becoming active, leading to new challenges in the voltage management, power flow management, network monitoring and control. These active networks need to be monitored and controlled much more compared to the past. But unfortunately the information technology for monitoring distribution networks has only been installed rather sporadically. Due to the intermittent energy supply of some renewable energy plants, power flow problems (overloads, masked overload) and voltage problems (voltage limit violations, voltage spreads) occurring in distribution networks need to be detected and solved. Therefore, an upgrade of these networks is necessary to avoid disruptions and severe damage. An upgrade with ICT and intelligence would transform these networks into Smart Grids. The operational management of such networks is a new and complex task for the
control center staff. The staff must take new types of decisions, will have new responsibilities, will deal with new types of problems and will have to operate the grid in a new way taking into account new information. Thus, it is important to develop tools for supporting the control center staff during the network operation. Additionally, it is important to increase the staff’s knowledge and skills to professionally operate Smart Grids and handle the new tasks. This can be achieved through training by using a dynamic network training system.

A dynamic network training system and some important tools for the operational management of Smart Grids have been developed, implemented and tested in this thesis. The implementation of models and functions was done under consideration of existing guidelines and laws. Future grids, strategies and operations can be tested risk-free. Decision making is supported by analyzing tools. The staff qualification and preparation for new tasks is done by an adequate operational training. The training is performed in an authentic manner and is risk-free. It is done using a dynamic network training system which visualizes the power grid on a standard workstation of a SCADA system and authentically simulates all network components including their interaction in real time. Network data, weather conditions and load profiles are easily declared. Different network emergencies, scenarios and strategies to solve problems can be considered. During this project, the network training system was used to prepare and train the control center staff of the DSO RMN in Darmstadt. The training was successful and the network training system was considered as a powerful tool with great potential.

The use of the network training system is not limited to the training of the control center staff. It can be used at colleges and universities as an illustrative simulation system to support learning besides the theoretical education. Furthermore, it can be used for demonstration purposes at conferences and seminars. Finally, the public, the policy and the regulatory authority can be made aware of certain issues through a clear demonstration of effects in real time. Thus, DSOs can justify and force an adaptation or improvement of laws.
8.2 Future Work

Based on the achievements in this thesis, the following points might be of very big importance for investigations and realizations:

- Development of a hardware based Grid Manager as described in Chapter 3. Once this is done, the next steps would consist of interconnecting Grid Managers and realize the data/information exchange as mentioned in Chapter 3. A power grid simulator (computer running a software for grid simulation) might be put in place to simulate an entire electrical grid and generate data. This electrical grid would be logically divided into grid areas which are each supervised and controlled by a Grid Manager and from which the respective Grid Manager gathers data and information.

- Development of grid operational strategies for the prevention of any deterioration of the supply quality, security and reliability as well as the avoidance of possible domino effects leading to possible blackouts, which might be caused by technical disturbances, failures and damages in the power grid and in the communication network linked to the power grid. Following might be considered:
  
  o Strategies for prevention, prediction, detection, fault tolerance, resilience and counteracting.
  
  o Fallback strategies especially for Grid Managers and SCADA systems if all other measures were not successful or not sufficient. Once activated, these grid control systems set and leave the power grid in a secure state.

- Development of security strategies in case of direct attacks and cyber-attacks on power grid infrastructures as smart meters, Grid Managers, SCADA systems and others:
  
  o Strategies for prevention, detection, resilience and counteracting.
  
  o Fallback strategies especially for Grid Managers and SCADA systems if all other measures were not successful or not sufficient. Once activated, these grid control systems set and leave the power grid in a secure state.

- Development and application of analytics delivering insights during power grid operation and planning. The structure and operation of a Smart Grid as presented in Section 3.2.2 offer a good basis for the use of analytics. Following analytics could be investigated and developed:
- Development of systems for assisting and supporting the control center staff in the network operation. These systems work autonomously, could interact with the user, rely on the data/information available and make use of the analytics too.

- As the implemented tools presented in Chapter 6 work well only for fully symmetrical networks, an extension of these tools or a re-implementation to obtain new variants for application to symmetrical and unsymmetrical networks should be undertaken. These variants are most suited for practical application for network operation due to the fact that electrical networks are not at any time always in a symmetrical state during operation. The results obtained and the actions proposed by these new tool variants would depend on the voltage and loading situation on each phase of the network.

- Development of further training scenarios for the training of the control center staff.
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APPENDICES

For sake of clarity, further appendices have been moved to the supplementary volume accompanying this thesis.

A1 Introduction to Kalman filtering

The Kalman filter, also known as linear quadratic estimation (LQE), is an algorithm which uses a series of measurements observed over time, containing noise (random variations) and other inaccuracies, and produces estimates of unknown variables that tend to be more precise than those that would be based on a single measurement alone. The Kalman filter is one among the tools which minimizes the variance of the estimation error. The algorithm works in a two-step process. In the prediction step, the Kalman filter produces estimates of the current state variables, along with their uncertainties. Once the outcome of the next measurement (necessarily corrupted with some amount of error, including random noise) is observed, these estimates are updated using a weighted average, with more weight being given to estimates with higher certainty. Because of the algorithm's recursive nature, it can run in real time using only the present input measurements and the previously calculated state.

In order to use the Kalman filter to estimate the internal state of a process given only a sequence of noisy observations, one must model the process in accordance with the framework of the Kalman filter. This means specifying the following matrices for each time step $k$.

$$A_{k} \quad \text{State transition model}$$

$$B_{k} \quad \text{Control input model}$$

$$H_{k} \quad \text{Measurement model relating the states to the measurements}$$

$$S_{u} \quad \text{Covariance of the process noise}$$

$$S_{v} \quad \text{Covariance of the observation noise or measurement noise}$$

State equation:

$$x_{k+1} = A_{k}x_{k} + B_{k}u_{k} + w_{k} \quad \text{Equation A1.1}$$
Output equation:
\[ z_k = H_k x_k + v_k \]  \hspace{1cm} \text{Equation A1.2}

In Equation A1.1 and Equation A1.2, A, B and H are matrices, k is the time index, \( x_k \) is the state of the system, \( u_k \) is the input to the system and \( z_k \) is the measured output. \( w_k \) and \( v_k \) are the noise processes. The variable \( w_k \) is called the process noise and \( v \) is called the measurement noise. Both of these are zero mean noise processes which generate random noise values with zero average. The Covariance of the process noise \( w \) is \( S_w \) and similarly, the covariance of the measurement noise \( v \) is \( S_v \). These quantities are usually vectors containing more than one element.

The vector \( x_k \) contains all the information about the present state of the system, but these may or may not be able to be measured directly. The elements of vector \( z_k \) are measurable and are functions of the state vector \( x_k \). Hence \( z_k \) used to obtain an estimate of \( x_k \). The problem with this is that the elements of \( z_k \) are error prone and need refining. Hence the available measurements in \( z_k \) are used to estimate the state of the system \( x_k \).

The biggest challenge with respect to the system model using the Kalman filter is to obtain a model of the process noise and of the measurement noise. Both these values have been defined to have zero mean. Then the covariance matrices \( S_w \) and \( S_v \) are developed, where:

\[ S_w = E(w_k w_k^T) \]  \hspace{1cm} \text{Equation A1.3}

and

\[ S_v = E(v_k v_k^T) \]  \hspace{1cm} \text{Equation A1.4}

Once the measurement noises have been defined, the concept of minimization of a cost function is applied (see supervised project [8]). With these state and output equations defined, a model of the Kalman filter is obtained.

The state of the filter is represented by two variables, \( x_k \) and \( P_k \) where \( x_k \) is the a posteriori state estimate at time k given observations up to and including time k, and \( P_k \) is the a posteriori error covariance matrix (a measure of the estimated accuracy of the state estimate).

The Kalman filter can be written as a single equation. However it is most often conceptualized as two distinct phases, Predict and Update. The predict phase uses the state estimate from the previous time step to produce an estimate of the state at the current time step. This predicted state estimate is also known as the a priori state.
estimate because, although it is an estimate of the state at the current time step, it does not include observation information from the current time step. In the update phase, the current a priori prediction is combined with current observation information to refine the state estimate. This improved estimate is termed the a posteriori state estimate. Typically, the two phases alternate, with the prediction advancing the state until the next scheduled observation, and the update incorporating the observation. They are expressed as follows:

Predict next state and error covariance:
\[
\hat{x}_k = A_k x_{k-1} + B_k u_k \tag{A1.5}
\]
\[
P_k = A_k P_{k-1} A_k^T + S_w \tag{A1.6}
\]

Update equations
\[
y_k = z_k - H_k \hat{x}_k \tag{A1.7}
\]
\[
S_k = A_k P_{k-1} A_k^T + S_v \tag{A1.8}
\]
\[
K_k = P_k H_k^T S_k^{-1} \tag{A1.9}
\]
\[
\hat{x}_k = \hat{x}_k + K_k (y_k) \tag{A1.10}
\]
\[
P_k = (I - K_k H_k) P_k \tag{A1.11}
\]

Upon closer inspection of the Kalman gain equation, it can be seen that if the measurement noise is large, $S_v$ will be large, consequently $K_k$ will be small. In simple terms, this would mean that the expression would reduce the importance given to the measurement $z$ when computing the next state estimate.

On the other hand if the measurement noise, $S_v$ is small, $K_k$ will be large, hence giving the term more importance.

A2  Exact Measurement Model

The exact measurement model for the state estimation is defined in both following subsections.
a  For Micro Grid with No Smart Meters

As no smart meters are present, it would be possible to use just the measurements from
MV/LV transformer as there would be no direct measurements within the network. The
measurement vector for this case could be expressed as:

\[ z = [P_{\text{transformer}} \quad Q_{\text{transformer}}]^T \]  \hspace{1cm} \text{Equation A2.1}

The active and reactive power of the energy feed-in transformer of the Micro Grid can
be modelled as the sum of active and reactive power injections from each of the
individual units including the losses in the transmission of power from each unit. This
can be expressed as:

\[ P_{\text{transformer}} = (P_{\text{injection}} + P_{\text{transmission}}) \]  \hspace{1cm} \text{Equation A2.2}
\[ Q_{\text{transformer}} = (Q_{\text{injection}} + Q_{\text{transmission}}) \]  \hspace{1cm} \text{Equation A2.3}

The transmission losses can be modelled as follows:

\[ S_{\text{transmission}} = S_{ij} + S_{ji} \]  \hspace{1cm} \text{Equation A2.4}

where \( S_{ij} \) is defined as:

\[ S_{ij} = P_{ij} + jQ_{ij} = V_i I_j^* \]  \hspace{1cm} \text{Equation A2.5}

This can be simplified, upon finding conjugate, as:

\[ S_{ij}^* = P_{ij} - jQ_{ij} = V_i^* I_j = V_i^* (V_i - V_j) Y_{ij} \]  \hspace{1cm} \text{Equation A2.5}

hence upon solving them taking the Cartesian form of the voltages and admittances:

\[ P_{ij} = V_i V_j^* \cos(\theta_i) - Y_{ij} V_i V_j \cos(\delta_i - \delta_j + \theta_j) \]  \hspace{1cm} \text{Equation A2.6}

and

\[ Q_{ij} = -V_i V_j^* \sin(\theta_i) + Y_{ij} V_i V_j \sin(\delta_i + \delta_j + \theta_j) \]  \hspace{1cm} \text{Equation A2.7}

Hence Equation A2.4 becomes:

\[ S_{\text{transmission}} = S_{ij} + S_{ji} = P_{ij} + jQ_{ij} + P_{ji} + jQ_{ji} = (P_{ij} + P_{ji}) + j(Q_{ij} + Q_{ji}) \]  \hspace{1cm} \text{Equation A2.8}

If \( j \) were considered to be the node at with the transformer is connected, then this would
provide the power taken for the transformer to transmit energy to the unit in relation to
the unit consumption.
The active and reactive power consumptions can be obtained from the load profiles of each unit. Hence a nonlinear exact model of the active and reactive power consumed by the transformer as a function of the individual consumptions of each unit, their voltage angles and magnitudes is obtained. Thus obtaining \( z \) as expressed in Equation A1.2:

\[
z_k = h_k(x_k) + v_k
\]

### b  For Micro Grid with Smart Meters

In the case where some smart meters are installed, it would be possible to improve upon the state estimate using the measurements of these smart meters.

The measurement vector would be modified to be as expressed in Equation 6.38 or Equation 6.39 depending upon the number of meters installed.

The transformer measurements can be expressed in the same method as in Equation A2.9.

There needs to also be included a relation between the state to the measurement of the smart meters. This can be obtained by the power flow equation,

\[
\overline{V}_i(\overline{I}_i) = \overline{V}_i \sum_k (\overline{V}_k Y_{ik}) = P_i + jQ_i \tag{Equation A2.10}
\]

thereby relating the active and reactive power injections of the units in the state to the voltage angle and voltage magnitude of the smart meter measurements. The reverse relation can also be obtained, i.e., a relation between the voltage angle and voltage magnitude of the units in the state to the active and reactive power injections of the smart meter measurements.

Thus, the Equations A2.9 and A2.10 would form the nonlinear exact measurement equation for the system as expressed in Equation A1.2:

\[
z_k = h_k(x_k) + v_k
\]
List of Publications


List of supervised thesis realized during the PhD


… and many semester final projects.