The Smart Power Cell Concept

A Novel System Architecture and Operational Concept for the Efficient, Secure and Stable Operation of Future Power Systems

Von der
Fakultät für Elektrotechnik und Informationstechnik
der
Technischen Universität Dortmund
genehmigte

Dissertation

zur Erlangung des akademischen Grades
Doktor der Ingenieurwissenschaften

vorgelegt von

Daniel Mayorga González, M. Sc.
aus Lima, Perú

Dortmund, 2021

Referentin:	Prof. Dr.-Ing. Johanna Myrzik
Korreferent:	Prof. Dr.-Ing. habil. Christian Rehtanz

Tag der mündlichen Prüfung: 22. Februar 2021

Abstract

This dissertation describes a novel architecture and operational concept for a future electric power system. The architecture and operational concept were developed as a solution to the technical challenges which result from the ongoing decommissioning of conventional power plants and the mass scale integration of distributed and renewable energy sources. In particular, the architecture aims at ensuring the efficient, secure and stable operation of a future power system by enabling the coordinated operation of its distribution and transmission grids. To this, in the first part of the dissertation, the Smart Power Cell concept is introduced. A Smart Power Cell is a subsection of the distribution domain of a future power system which is supervised and controlled by an ICT-based monitoring and control system. A Smart Power Cell can be controlled to adapt its dynamic behaviour on demand an thus be integrated into the operation of the transmission network. The dissertation then deals with the modelling and simulation of a power system organized according to the developed concept. Besides, methods for the description of the flexibility of Smart Power Cells to support the operation of a transmission network are described. In addition, a control scheme for controlling the power which a Smart Power Cell exchanges with the transmission network is presented. Finally, the developed methods are tested by means of steady-state and dynamic simulations using a combined transmission-distribution test system designed for this purpose. The dissertation closes with a summary of the main contributions and a discussion of the research efforts required to bring the Smart Power Cell concept into life.

Kurzfassung

Die vorliegende Dissertation beschreibt eine neuartige Architektur und ein Betriebskonzept für ein zukünftiges elektrisches Energieversorgungssystem. Die Architektur und das Betriebskonzept wurden als Lösung für die technischen Herausforderungen entwickelt, die sich aus der laufenden Stilllegung konventioneller Kraftwerke und der Integration verteilter und erneuerbarer Energieerzeuger ergeben. Die Architektur zielt darauf ab, den effizienten, sicheren und stabilen Betrieb eines zukünftigen Energieversorgungssystems zu gewährleisten, indem sie den koordinierten Betrieb seiner Verteil- und Übertragungsnetze ermöglicht. Dazu wird im ersten Teil der Dissertation das Konzept der Smart Power Cell vorgestellt. Eine Smart Power Cell ist ein Teilnetz der Verteilnetzebene eines zukünftigen Energieversorgungssystems, das von einem ICT-basierten Überwachungs- und Steuerungssystem überwacht und gesteuert wird. Eine Smart Power Cell kann so gesteuert und geregelt werden, dass ihr dynamisches Verhalten bei Bedarf angepasst und somit in den Betrieb des Übertragungsnetzes integriert werden kann. Im zweiten Teil befasst sich die Dissertation mit der Modellierung und Simulation eines Energieversorgungssystems, das nach dem zuvor entwickelten Konzept organisiert ist. Auf dieser Basis werden dann Methoden zur Beschreibung der Flexibilität von Smart Power Cells zur Unterstützung des Betriebs eines Übertragungsnetzes entwickelt und präsentiert. Auch eine Regelungsstruktur zur Anpassung der Leistung, die eine Smart Power Cell mit dem Übertragungsnetz austauscht, wird entworfen und vorgestellt. Schließlich werden die entwickelten Verfahren mittels stationärer und dynamischer Simulationen mit einem dafür konzipierten kombinierten spannungsebenenübergreifenden Testsystem analysiert. Die Dissertation schließt mit einer Zusammenfassung der wichtigsten Beiträge und einer Diskussion des notwendigen Forschungsbedarfs, um das Smart Power Cell Konzept in Zukunft zu realisieren.

Danksagung

An erster Stelle möchte ich mich bei meiner Doktormutter Frau Prof. Dr.-Ing. Johanna Myrzik ganz herzlich bedanken. Sie ermöglichte mir die Promotion am Institut für Energiesysteme, Energieeffizienz und Energiewirtschaft (ie^3) der Technischen Universität Dortmund und hat mit wertvollem Feedback, konstruktiver Kritik und einem sehr engagierten Einsatz zum Gelingen dieser Arbeit maßgeblich beigetragen. Für das entgegengebrachte Vertrauen, die visionären Diskussionen und die inspirierende Betreuung bin ich ihr sehr dankbar.

Ebenso möchte ich mich bei Prof. Dr.-Ing. Christian Rehtanz für die Übernahme des Koreferats und den intensiven fachlichen Austausch bedanken. Nach dem Universitätswechsel von Prof. Dr.-Ing. Johanna Myrzik ermöglichte er mir am ie^3 die Erarbeitung meiner Dissertation unter optimalen Bedingungen fortzusetzen. Hierfür möchte ich ihm einen besonderen Dank aussprechen.

Allen Mitarbeitern und Studierenden des ie^3 danke ich für die tolle Zusammenarbeit und den intensiven und spannenden Austausch. Die unzähligen Diskussionen und gemeinsame Projekte mit Euch waren für das Gelingen dieser Arbeit entscheidend. Ich habe unsere gemeinsame Zeit sehr geschätzt und genossen und nehme unzählige schöne Erinnerungen mit, die mich für den Rest meines Lebens begleiten werden. Insbesondere möchte ich mich namentlich bei Jonas Hinker, Annika Schurtz, Marie Kloubert, Stefan Dalhues, Ulf Häger, Sebastian Liemann, Marcel Klaes, Andreas Kubis, Lena Robitzky, Sven Christian Müller, Dominik Robin, Jan Hachenberger und Julian Kemper bedanken.

Zudem möchte ich mich für die Durchsicht des Manuskripts sowie die konstruktive und sehr wertvolle Kritik bedanken bei Jannik Zwartscholten, Dennis Schmid, Fabian Erlemeyer, Gabriel Ortiz, Marilyn Asmah, Matthias Meißner und Zita Hagemann.

Schließlich möchte ich meiner Familie und insbesondere meinen Eltern für ihre ständige und uneingeschränkte Unterstützung während meines gesamten Werdegangs danken.

Vielen lieben Dank für alles!

Dortmund, Februar 2021

Daniel Mayorga González

Contents

Abbreviations

ADN Active Distribution Network

CVLCM Cross Voltage Level Control Method

CPCU Controllable Power Conversion Unit

DG Distributed Generator

DSC Discrete Switching Component

DSO Distribution System Operator

EMT Electromagnetic Transient

FACTS Flexible Alternating Current Transmission Systems

FOR Feasible Operation Region

HV High Voltage

HVDC High-Voltage Direct Current

IB Interconnection Bus

ICT Information and Communications Technology

IPF Interconnection Power Flow

LV Low Voltage

MACS Monitoring and Control System

MV Medium Voltage

NPCU Non Controllable Power Conversion Unit

OLTC On Load Tap Changer

OLTC On Load Tap Changer

PCU Power Conversion Unit

PPO Power Plant Operator

RMS Root Mean Square

SPC Smart Power Cell

TSO Transmission System Operator

TG Transmission Grid

T-D Transmission-Distribution

1 Introduction

Due to the large-scale integration of renewable energy sources and the associated decommissioning of conventional power plants, electric power systems are undergoing a drastic transformation. In Germany, for instance, the federal government has set the goal to generate until 2050 at least 80 % of the electric power consumed in the country by renewable energy sources [33] and plans, in this context, to decommission all coal-fired power plants currently in operation until 2038 [34]. In addition, mainly due to safety concerns, the government has decided to decommission all nuclear plants within the German territory until 2022 [36]. Worldwide, similar measures are being taken and it can be expected that in the next years this transition will speed up.

This radical transformation of one of the most complex systems humanity has ever built will lay the foundation for ending the dependence of modern societies on fossil fuels and thus pave the way to a more sustainable and environmentally friendly future. However, until now, there is no concrete action plan to achieve such an objective and there is still a wide range of unprecedented challenges which need to be overcome.

One of the main technical challenges associated with the decarbonisation of the electric power system is the substitution of conventional power plants by a huge number of distributed generators without jeopardising the operability, security and stability of the system. The conventional power plants, which are planned to be decommissioned in the next decades, have several properties which are - today - essential for the efficient and secure operation of the system [28, 54, 60]. Up to now, it is still not clear, how a future power system with a very low share of conventional power plants and a very high penetration level of renewables can be operated [16, 23].

In state-of-the-art power systems, the grid is "formed" by the conventional power plants which, due to their physical properties and controllers, are able to determine the frequency and voltage behaviour of the system. Besides, in regard to the real-time operation of the system, conventional power plants participate in several essential operational interventions which are required for (i) corrective congestion management, (ii) balancing of generation and load, (iii) system optimization and (iv) system restoration purposes after blackouts. In addition, conventional power plants also play a predominant role in regard to the operational planning of the system. In this context, one of the most significant tasks is to find generation schedules of conventional power plants by means of a market-driven process such that the entire (forecasted) electric demand is served without violating system security and stability limits in the most economical way possible.

Due to these facts, it is not an overstatement to say that conventional power plants are today the backbone of the operability, security and stability of electric power system. Thus, in the context of the decarbonization of the electric sector, answering the following question in time becomes a matter of urgency:

> How can a future low-emission power system be structured, planned and operated so that its efficiency, security and stability can continue to be guaranteed when most conventional power plants - which today are the foundation for the operability and stability of the system - will no longer be in operation?

In the last two decades, huge research efforts have been undertaken to solve this problem and significant progress has been achieved. However, there are still many problems that have not yet been solved, and there is still a great deal of uncertainty concerning the path that system development needs to take.

What is clear so far is that in future distributed generators, storages and flexible loads within all voltage levels will need to participate in the operation of the system and in the provision of ancillary services which also will lead to the necessity of operating transmission and distribution networks in a coordinated way [15, 47]. This has already been recognized by industry and academia resulting in many contributions which suggest e.g. methods to involve distributed resources in the operation of the system, e.g. [72, 87, 91] and discuss approaches for the coordinated operation of distribution and transmission grids, e.g. [5, 20, 21, 22, 31, 44, 51, 55, 56, DM12, 83, 90, 96, 99, 100, 104].

Thanks to the substantial research work which has been carried out in this area over the last decades worldwide, we are more and more serene in answering the question posed above. However, it has to be mentioned that the majority of the related work published in the present tends to focus on very specific problems while the big picture is often overlooked. As a consequence, to this day, a holistic system architecture and a comprehensive operational concept for the efficient, secure and stable operation of a future fossil fuel independent power system with a very high share of renewables and distributed generators is still missing.

1.1 Objectives

As a contribution to close the previously identified research gap, this dissertation is intended to achieve the following objectives:

- Investigate the role of conventional power plants regarding the efficient, secure and stable operation of contemporary power systems and discuss why a fundamental reorganization of the system and its operation is required if these plants are decommissioned in a large scale and replaced by a large number of distributed and renewable generators.
- Identify the structural changes and operational modifications needed to ensure the efficient, secure and stable operation of future power systems.
- Develop, describe and investigate a new architecture and operational concept for a future low-emission power system, which is intended to enable its efficient, secure and stable operation.
- Review state-of-the-art modelling and simulation methods for the investigation of the behaviour of electric power systems and asses which modifications are required to apply them in order to study the behaviour of a system organized according to the new developed operational concept.
- Describe a power system model which can be used for designing and investigating methods and control schemes which can be applied within the context of the developed power system architecture and operational concept.
- Develop and investigate methods and control schemes which can be applied within the context of a power system organized according to the developed concept.
- Test the developed methods and concepts by means of steady-state and dynamic simulations in a combined transmission-distribution power system model of a system organized according to the developed concept.

1.2 Structure and research design

In order to achieve the objectives listed above and to provide insight in the research work which was conducted over the last 5 years in this regard, this dissertation is organized in eight chapters, which are briefly described in the following:

Chapter 1: Introduction

This chapter gives an overview of the motivation and objectives of the dissertations and is intended to serve as a reading guide for readers which are interested in specific problems, methods and solutions described and want to have an overview on the contents treated before "jumping" to their section of interest.

Chapter 2: The role of conventional power plants in the operation of contemporary power systems

This chapter is intended to give an answer to the following research question:

> What role do conventional power plants play in the efficient, safe and stable operation of today's power system and what consequences can be expected if these plants are decommissioned without making fundamental changes to the way the system is organised and operated?

To answer this question, first, the architecture and basic operating principles of state-of-the-art power systems are briefly reviewed. Subsequently, the theoretical background associated with the mathematical description of the operating conditions of a power system is discussed and terminology related to the concepts of power system stability and power system security introduced. Then, the chapter gives an overview of the operational interventions which are required to enable an efficient, stable and secure operation of a state-of-the-art power system and discusses what role conventional power plants do play in these interventions. Subsequently, the chapter discusses the need for developing a new architecture and operational concept due to the decommissioning of conventional power plants and the large scale integration of renewable and distributed generation. Finally, the identified need for developing a new architecture and operational concept is compared with the objectives and results of contemporary research and a research gap analysis is conducted.

Chapter 3: The Smart Power Cell Concept

This chapter aims at answering the following research question:

> How can a future low-emission power system with an extremely high number of distributed and renewable generators and very few or no conventional power plants be structured and operated such that its efficiency, security and stability can continue to be guaranteed?

In response, the chapter describes and investigates a new architecture and operational concept for a future low emission power system, which is intended to enable its efficient, secure and stable operation. The developed architecture and operational concept, which from now on will be referred to as "The Smart Power Cell Concept", is based on the idea of organizing the distribution network level in supervised and controlled grid subsections called Smart Power Cells (SPCs), which can adapt their dynamic behaviour on demand and thus, participate in the operation of the transmission network. By reorganizing the distribution network level according to the SPC concept, the coordinated operation of transmission and distribution networks can be enabled. This makes possible that distributed generators, flexible loads and storages connected over all voltage levels participate in the operation of the entire system in a coordinated way. In this manner, the interventions which were identified in chapter 2 and are essential for the efficient, secure and stable operation of today's system and currently rely on conventional power plants can be fully substituted.

Chapter 4: Modelling and simulation of contemporary and future power systems

In this chapter, the following research question is addressed:

> How can a future low-emission power system be modelled such that new architectures, methods and control schemes can be developed, designed and tested by means of steady-state and dynamic simulations?

To answer this question, the chapter first addresses state-of-the-art models and methods used to study the behaviour of a power system by means of steady-state and dynamic simulations. Subsequently, simplifications which are common practice today, but seem to be unfeasible for the analysis of a future power system organized according to the developed SPC concept are discussed and modifications to enable this aim are identified. Finally, the chapter closes with a general description of a model which can be used to study the behaviour of future power systems organized according to the SPC concept. In particular, the developed model enables to reproduce and study the interactions of the transmission network with the Smart Power Cells connected to it - which can also be thought of as transmission-distribution interactions. To this, not only the transmission network level and the conventional power plants of a power system are modelled in detail, as it is common practice today. Instead, the mathematical description of the SPCs along with their components needs are in the centre of attention. Besides, the model also represents the weather dependency of SPCs and the impact of cross-voltage-level control schemes. Finally, by means of a very simple communication model, the impact of ICT processes is taken into account.

Chapter 5: The flexibility of a Smart Power Cell to support the operation of a transmission network

This chapter focuses on the description of two methods that have been developed to assess the extent to which SPCs can support the operation of the transmission network by adjusting their IPFs. The term IPF is used in this dissertation to refer to the apparent power flow exchanged at a moment in time by the transmission network and a particular SPC.

The chapter aims at answering the following research question:

> How can the flexibility of an SPC to control its IPF be determined so that a TSO can take into account the contribution of the SPCs in the day-ahead and intra-day operational planning of a future power system organised according to the Smart Power Cell concept?

Answering this question is substantial because, in a future power system organized according to the SPC concept, whenever the state of the transmission network needs to be adjusted due to efficiency, security or stability concerns, the main source of operational flexibility will not be provided by conventional power plants. Instead, SPCs will be the main sources of operational flexibility to impact the active and reactive power balance of particular transmission system buses. Thus, in future, the information regarding the flexibility of an SPC could be used by a TSO to plan in advance in what extent each SPC connected to its responsibility area will participate in the operation of the system by adjusting its IPF.

The chapter describes in this context two methods which are intended to describe the flexibility of an SPC depending on time-variant external influencing factors and operational constraints: Method 1 aims at determining the flexibility of an SPC under the premise of perfect information, i.e. when all modelled influencing factors are known. Method 2, on the other hand, is meant to be used to estimate in advance the flexibility that an SPC will have in future time intervals using forecasts of time-variant influencing factors under consideration of uncertainty by a probabilistic approach. The applicability of the proposed methods is demonstrated in three case studies at the end of the chapter.

Chapter 6: Control scheme for Interconnection Power Flow Control of a Smart Power Cell

This chapter focuses on the IPF control of an SPC and describes in this context a control scheme which was developed to control the active and reactive IPF of an SPC according to set-points issued by a superimposed monitoring and control system at the transmission level. The chapter is intended to answer the following research question:

> How can the behaviour of SPC components (distributed generators, flexible loads, storages, etc.) be controlled such that the active and reactive IPF of an SPC can be adjusted on demand to follow set-points provided by the transmission network?

To answer this question, the chapter describes a control scheme which is able to coordinate the behaviour of distributed generators, storages and flexible loads within an SPC in order to control its IPF on demand. In particular, the control scheme is designed to achieve the control objective without engendering the security and stability of the SPC. By this, only changes of the IPF are realized which do not violate pre-established security constraints (e.g voltage and loading limits). The developed control scheme is tested at the end of the chapter by means of time-domain simulations. To this, a test system (dynamic model of an SPC consisting on a medium voltage grid, distributed generators, storages, conventional and flexible loads, circuit breakers and On Load Tap Changer (OLTC) transformers) is provided and simulations are conducted. The simulation results show that the developed control scheme can be used to adapt the behaviour of an SPC on demand and by this change its IPF aiming at supporting the transmission grid in operational interventions such as corrective congestion management, voltage support, balancing of generation and load and system optimization.

Chapter 7: Dynamic behaviour of a power system organized according to the Smart Power Cell Concept

A system wide implementation of the Smart Power Cell concept would have drastic implications on the way a power system dynamically behaves. Thus, when control schemes which are aimed to be applied within the Smart power cell concept are designed and tested, it is substantial to study and consider their impact on the dynamics of the entire system. As a contribution to this problem, this chapter is devoted to answering the following research question:

> How can the impact which SPCs have on the dynamic behaviour of a future power system be studied an analysed in order to design and test the required control schemes under consideration of wide are dynamics?

In order to answer this question, first, a combined transmission-distribution test system, which was developed to design and test control schemes for a future power system organized according to the SPC concept, is described. The developed test system is composed of a transmission network, five conventional distribution networks and eight SPCs, which are controlled by the control scheme described in section 6. Then, in order to study the dynamic behaviour of the developed test system, two selected case studies are presented which aim to demonstrate how a power system organized according to the SPC concept would dynamically behave if the behaviour of its SPCs is coordinated by a superimposed monitoring and control system to support the operation of the transmission network. In the first case study, it is shown how the SPCs of the developed test system are coordinated to solve a congestion at the transmission network level. Further, in the second case study, the impact of a short circuit on the dynamic behaviour of the test system is investigated. Besides, the case study also demonstrates how a voltage problem which was originated by the short circuit can be solved by coordinating the behaviour of the SPCs connected to the system.

Chapter 8: Conclusions and outlook

In this chapter, a summary of the dissertation and a synthesis of the main contributions and conclusions is provided. Besides, the chapter discusses possible shortcomings of the ideas, concepts, methods and control schemes presented. Finally, the chapter closes with an outlook regarding the required research work to bring the SPC concept into life.

2 The role of conventional power plants in the operation of contemporary power systems

Today, conventional power plants play a predominant role in the operation of electric power systems. In future, however, conventional power plants will be decommissioned and substituted by a huge number of distributed generators. This transition towards an environmentally friendly system does not only require significant changes in the established infrastructure. In fact, it can be expected that the complexity of the system will substantially increase and its dynamic behaviour will fundamentally change making the development of new planning, control and operation strategies and concepts a matter of urgency. In this chapter, the role of conventional power plants in the current operation of the system is reviewed and the need for a new system architecture and operational concept discussed. In particular, the chapter is devoted to answering the following question:

> What role do conventional power plants play in the efficient, safe and stable operation of today's power system and what consequences can be expected if these plants are decommissioned without making fundamental changes to the way the system is organised and operated?

To answer this question, the chapter begins with a brief review of the architecture and basic operation principles of contemporary power systems. The theoretical background associated with the mathematical description of the operating conditions of a power system is subsequently discussed and terminology related to the concepts of power system stability and power system security introduced. The chapter further gives an overview of the operational interventions required to enable an efficient, stable and secure operation of a state of the art power system and additionally discusses the role of conventional power plants in these interventions. Finally, the chapter closes with a discussion of the need for developing a new architecture and operational concept due to the decommissioning of conventional power plants and the large scale integration of renewable and distributed generation. Note that some contents of the chapter have already been addressed in previous work [DM2, DM5, DM9, DM10, DM11, DM13].

2.1 Structure and basic operation principles of contemporary power systems

The traditional body of literature devoted to power systems (e.g. [59], [3], [52], [41],[82], [19]) usually tends to divide the power system infrastructure into three or four domains - generation, transmission, distribution and supply - and states that the purpose of the system is to supply the loads (customers) with electrical power produced by generating units.

The hierarchical architecture of a contemporary system is shown in figure 2.1. According to this structure, the major part of the power fed into the grid is injected by a few conventional power plants operated at voltage levels of 10 - 20 kV. These plants transform thermal or hydraulic energy by means of a synchronous generator into electric power and are connected to the transmission network via a step-up transformer, which increases the voltage (and reduces the current) to inject the generated electric power into particular substations of the transmission grid. The transmission grid, which is composed of a meshed

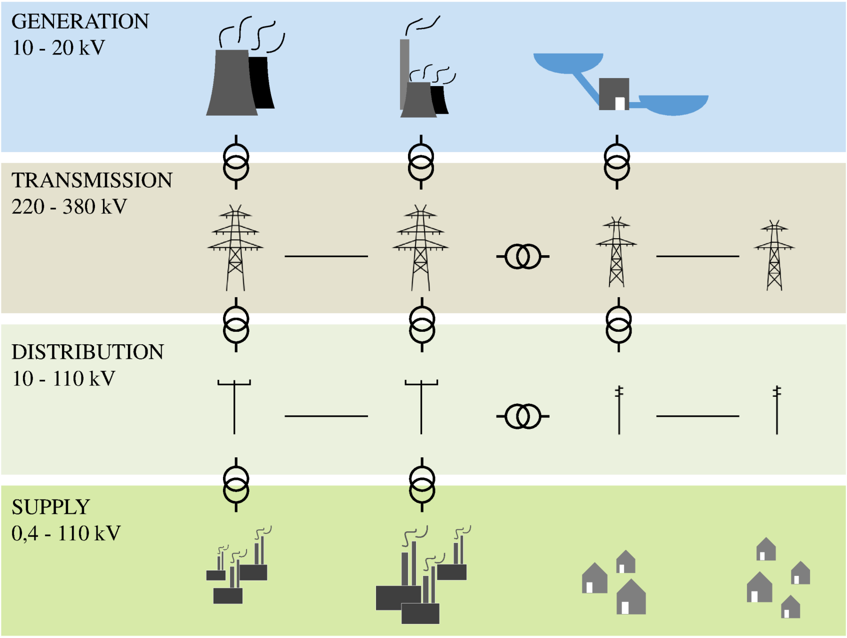


Figure 2.1: Hierarchical architecture of a contemporary power system

system of transmission lines operated at high and extra-high voltages (220 - 380 kV), enables the transmission of the injected power over long distances to "load centres" which are substations located, for instance, nearby or within cities or next to a group of large industrial loads. In these substations, electric power is fed into distribution networks by step down transformers which reduce the voltage to distribution levels (0.4 - 110 kV). These transformers are usually equipped with an OLTC which enables the adjustment of the transformer ratio without interruptions. Thus, the voltage at the low voltage side of the transformer can be kept near its rated voltage even if the voltage of the high voltage side changes. The power fed into distribution networks is delivered from the transmission-distribution coupling points to the customers via distribution network lines and cables. In the case of large industrial or commercial loads, the power is directly supplied at the medium voltage level. In residential and low-density commercial areas, the voltage is further reduced by means of distribution transformers (e.g. 10/0.4 kV).[39]

In order to generate, transmit and distribute power in high quality, with high efficiency, in an economic way and with the minimum number of interruptions possible, the system is supervised and operated by several system operators. These operators - Transmission System Operators (TSOs), Distribution System Operators (DSOs), Power Plant Operators (PPOs), etc. - are responsible for the interventions required for the optimal and secure operation of the infrastructure of the power system. In today's power systems, TSOs are responsible for the security of supply of their responsibility areas, and to this, assume the coordination of actions of all involved parties (DSOs, PPOs and themselves) associated with their control areas [25, 26, 28, 29, 30]. In this context, TSOs need to ensure that generation, transmission and distribution capacity is sufficient to supply the system loads in the long and short term complying with the following main technical criteria: [25, 26, 28, 29, 30, 97]

- The system frequency has low fluctuations and is continuously regulated and maintained nearby its nominal value (e.g. 50 +/- 0.05 Hz in Europe).
- The voltages of all buses have low fluctuations and are kept within a pre-established voltage range.
- System lines, cables and other components are not overloaded (Thermal limits are respected).
- Harmonics in the voltage are maintained below a pre-established threshold.
- The system is resilient against outages of network elements or other contingencies (after any contingency steady and dynamic stability is given and

the operating point remains within permissible operating ranges).

The fulfilment of these technical criteria is a challenging undertaking that requires that all the components and subsystems of the electric power system are operated in a coordinated, secure and stable way. Otherwise, power system instability could unfold leading to the collapse of parts or even the entire power system. To avoid such a scenario, system operators need to continuously monitor the operating conditions of the system and ensure that the system is operated within secure and stable operation regions. In the following subsections, the fundamental terminology related to the concepts of power system stability and security is briefly reviewed.

2.2 Operating conditions, stability and security of power systems

This section gives an overview of the theoretical background related to the mathematical description of the operation of a power system. Further, it also deals with fundamental terminology and concepts required to understand the concepts of power system stability and security. The section concludes by addressing a standard framework for the classification of power system operational states regarding the security of supply.

2.2.1 Mathematical description of the operating conditions of a power system

The operating conditions of a power system can be described by its operating quantities which are physical quantities that can be measured or calculated [60, 65, 73]. The evolution of these quantities over time can be simulated using a mathematical model composed of differential-algebraic equations. A general formulation of such a model can be given as [65]

$$\dot{\mathbf{x}} = \boldsymbol{f}(\mathbf{x}, \mathbf{y}, \mathbf{u}, t) \tag{2.1a}$$

$$\mathbf{0} = \boldsymbol{g}(\mathbf{x}, \mathbf{y}, \mathbf{u}, t). \tag{2.1b}$$

Here $\mathbf{x}$ ($\mathbf{x} \in \mathbb{R}^{n_x}$) is the state vector, $\mathbf{y}$ ($\mathbf{y} \in \mathbb{R}^{n_y}$) the algebraic variable vector, $\mathbf{u}$ ($\mathbf{u} \in \mathbb{R}^{n_u}$) the input vector and t the time.

When an initial condition ($\mathbf{x} = \mathbf{x_0}$) is given and the trajectory of the input vector $\mathbf{u}$ is known, the trajectories of the vectors $\mathbf{x}$ and $\mathbf{y}$ can be computed by

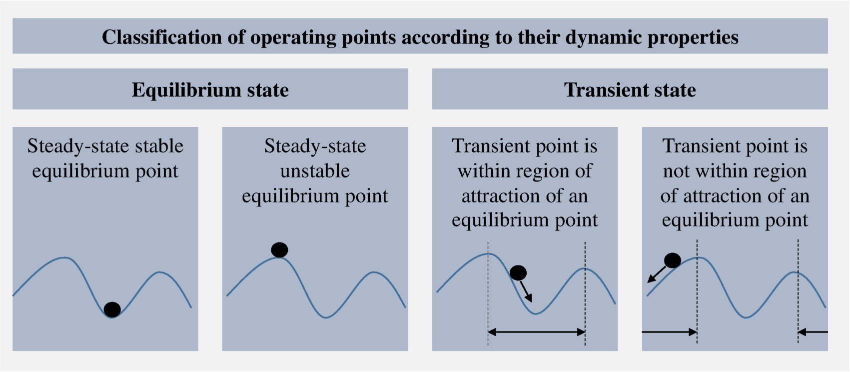


Figure 2.2: Classification of operating points according to their dynamic properties

means of numerical integration. Thus, the behaviour of the system in normal but also in contingency conditions can be studied and analysed. [60]

The vectors $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{u}$ span the multidimensional parameter space $\mathcal{P}$. The operating condition of a system at a particular moment can be described as a point in this space, which is usually referred to as the operating point of the system. A sequence of operating points over a time period $t^0 \leq t \leq t^{\text{end}}$ is called a trajectory.

A system is considered to be in a steady-state when for a particular point in $\mathcal{P}$ the expression

$$\dot{\mathbf{x}} = \mathbf{0} \tag{2.2}$$

applies. Points for which eq. 2.2 is true are considered to be equilibrium points of the system 2.1. [66]

For all remaining operating points where

$$\dot{\mathbf{x}} \neq \mathbf{0}, \tag{2.3}$$

the system is considered to be in a transient state. [66]

The operating points within $\mathcal{P}$ can be further classified as figure 2.2 shows. Equilibrium states can be classified into steady-state stable and steady-state unstable equilibrium points. An equilibrium point is considered to be steady-state stable if following any small disturbance the system reaches a steady-state operating condition which is identical or close to the pre-disturbance operating condition [73]. On the other hand, an equilibrium point is considered steady-state unstable if following any small disturbance the operating point which the system would adopt deviates significantly from the original equilibrium point. [73] Transient operating points, which are points which belong to a trajectory describing a dynamic transition of the system, can be classified based on whether they belong to the region of attraction of a steady-state stable equilibrium point or not. The region of attraction of a particular steady-state stable equilibrium point is the set of all transient operating points which are dynamically attracted to that particular equilibrium point [95]. If a system adopts a transient operating point within the region of attraction of a particular steady-state stable equilibrium point, the system adopts after an endless period of time that equilibrium point by a dynamic transition [95]. On the other hand, transient operating points which are not located within the region of attraction of any equilibrium point trigger a dynamic transition in which the operating point drifts away [95].

2.2.2 Power system stability

An important prerequisite for the suitable operation of a power system is its stability. According to the IEEE/CIGRE Joint Task Force on Stability Terms and Definitions of 2004 [53] "power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."[53] Maintaining power system stability is of major importance for the suitable operation of the system since if instability unfolds, the system can adopt an unsafe behaviour which in severe cases can lead to the collapse (blackout) of the whole or parts of the system [60].

A prerequisite for power system stability is that the operating point of the system remains within the system's region of attraction $\mathcal{R}(\mathcal{G})$ [95]. Here, $\mathcal{G}$ denotes the set of all existing steady-state stable equilibrium points of a system, which is also known as the set of attractors of a system. The region of attraction $\mathcal{R}(\mathcal{G})$ is the set of operating points which are either steady-state stable equilibrium points belonging to $\mathcal{G}$ or transient operating points which are dynamically attracted to a steady-state stable equilibrium point [95]. Thus, as long as the system remains within $\mathcal{R}(\mathcal{G})$, the system can always return to a steady-state stable equilibrium point.

When a power system is subject to a disturbance, its operating point changes abruptly and the system adopts a transient state [66]. As long as this new operating point remains within the region of attraction $\mathcal{R}(\mathcal{G})$, it can be expected

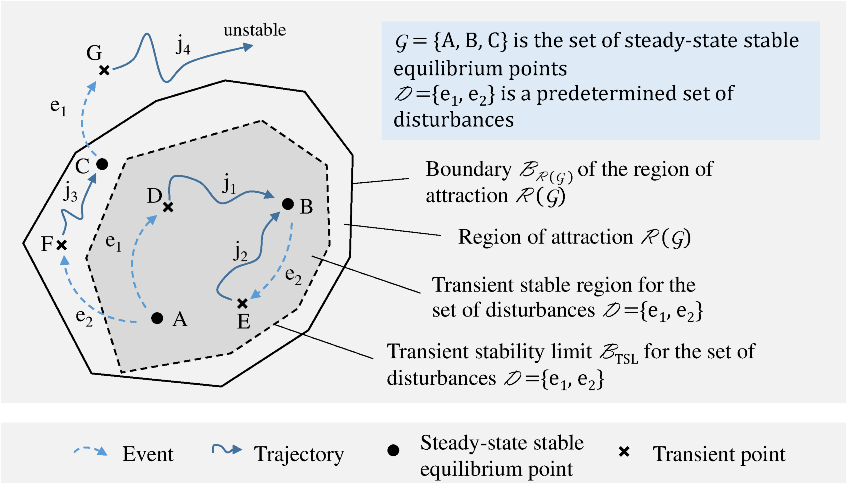


Figure 2.3: Schematic overview of fundamental stability-related concepts for the characterization of the parameter space of a power system

that the system will return to a steady-state stable point of equilibrium after a limited period of time. Given this, the system is considered to be transient stable for that particular initial condition and that particular disturbance [73]. In contrast, when the operating point which the system adopts after a particular event is not located within $\mathcal{R}(\mathcal{G})$, the system's operating point is likely to drift away exposing the system to the risk of equipment damages, cascading events and collapse [66]. In this case, the system is considered to be transient unstable for that particular initial condition and disturbance [73]. Control actions also change the operating point of a system triggering a dynamic transition which starts with a new transient state. Control actions which lead to a transient state with a trajectory outside the region of attraction $\mathcal{R}(\mathcal{G})$ are transient unstable and need to be avoided.

In order to reduce the probability of occurrence of system collapse, the system needs to be designed and operated in such a way that instability can be avoided even if disturbances occur. In this context, however, it is important to notice that resilience to all kind of disturbances (especially disturbances taking place in parallel) is impossible to achieve. In practice, therefore, the system is designed to be resilient to a pre-established set of disturbances with a high likelihood of occurrence [28]. For simplicity, the set of disturbances a power system is designed to be resilient to will be referred to as the predetermined set of disturbances

$\mathcal{D}$. Once such a set of disturbances with a high likelihood of occurrence has been defined for a particular system, it can be verified (e.g. by simulation) if a particular equilibrium point is transient stable for that set of disturbances or not. Following this idea, the steady-state stable equilibrium points of a system can be classified into two sets:

- The set $\mathcal{K}$ which is the set of equilibrium points which are transient stable for the set of disturbances $\mathcal{D}$ and
- the set $\mathcal{L}$ which is the set of equilibrium points which are transient unstable for the set of disturbances $\mathcal{D}$

This distinction between equilibrium points can be used to characterize the multidimensional parameter space $\mathcal{P}$ in relation to stability for a particular predetermined set of disturbances $\mathcal{D}$. If a system needs to be resilient to a disturbance belonging to the set $\mathcal{D}$, then the system's operating point needs to remain either at an equilibrium point within the set $\mathcal{K}$ or in the region of attraction $\mathcal{R}(\mathcal{K})$. The system can in theory also be operated within $\mathcal{L}$ but in this case, a disturbance belonging to $\mathcal{D}$ could trigger an unstable dynamic transition.

A schematic overview of the concepts explained above is illustrated in Figure 2.3. For visualization purposes, a two-dimensional representation inspired on [48] was chosen, however, it is important to notice that $\mathcal{P}$ is, in fact, a multidimensional space. The figure shows a schematic representation of the region of attraction $\mathcal{R}(\mathcal{G})$ of a fictitious system which only has three steady-state stable equilibrium points. Here, $\mathcal{G} = \{A, B, C\}$ is the set of all existing steady-state stable equilibrium points. In case the system adopts a new operating point within $\mathcal{R}(\mathcal{G})$ due to a control action or a disturbance, the system's operating point will be attracted to one of the equilibrium points belonging to $\mathcal{G}$ and the system will remain stable. However, if a control action or disturbance leads to a new operating point outside $\mathcal{R}(\mathcal{G})$ the system will lose its stability [48]. In the assumption that the system is required to stay stable for the predetermined set of disturbances $\mathcal{D} = \{e_1, e_2\}$, the system needs to be operated within the darker region of the multidimensional parameter space $\mathcal{P}$. As long as the system remains in this region - which is the transient stable region for the set of predetermined disturbances $\mathcal{D}$ - the system will remain stable, even if one of the disturbances which belong to $\mathcal{D}$ takes place. Thus, even though the operating point C is within $\mathcal{R}(\mathcal{G})$, this state has to be avoided since the event e_1 would make the system lose its stability.

Summary As stated in the previous lines, a power system can adopt points of operation within the multidimensional parameter space $\mathcal{P}$. These operating points are either equilibrium points or transient points. Equilibrium points can be steady-state stable or unstable. Steady-state stable operating points are surrounded by regions of attraction. Transient operating points within regions of attraction trigger a dynamic transition with a trajectory which ends in an equilibrium point. Transient operating points which are not inside any region of attraction lead to an unstable behaviour of the system which is characterized by drifting operating points. If the system needs to be resilient to a predetermined set of disturbances, then the system needs to remain in the transient stable region for that particular disturbance set. In that case, system stability is not lost when a disturbance belonging to the predetermined set of disturbances takes place.

2.2.3 Operational security limits

The operational space of a power system is not only restricted due to stability concerns. In addition, a power system is further restricted due to [25, 28, 30]

- thermal limits and
- voltage limits.

Thermal limits are restrictions of the operational space aimed to avoid the damage of power system equipment such as lines and cables due to high temperatures caused by thermal losses [28, 30]. These limits result from the physical properties of components and are established by equipment producers and/or system operators. The violation of thermal limits can lead to component failures, however, in general, the system is designed in such a way that protection schemes can intervene beforehand to prevent irreversible component damage. Protection actions (e.g. disconnection of a transmission line) can in severe cases initiate a succession of events with the potential of unfolding instability and causing a system collapse. When such an event takes place three scenarios can follow: [28, 30]

- the system adopts a new transient operating point within its region of attraction (the system is transient stable for that disturbance or event) and regains an equilibrium point which does not violate any operational security limit.
- the system adopts a new transient operating point within its region of attraction and regains an equilibrium point which violates at least one operational security limit.
- the system adopts a new transient operating point outside the system's

region of attraction causing the operating point of the system to drift away until further protection actions take place or the system collapses.

Due to the risk of cascading events which could lead to an unstable behaviour, the operating point of the system needs to remain in a sub-region of the space $\mathcal{P}$, such that thermal limits are continuously respected [28].

Voltage limits are restrictions of the operational space of a power system intended to avoid the voltage amplitude of a particular network bus or the phase shift between two buses leave a predetermined range [28, 30]. These limits are predetermined by the system operator and are required to ensure the proper functioning of the equipment installed at the different voltage levels of the system. Voltage limits are necessary because power system equipment and the system as a whole are designed to operate within particular voltage ranges. When voltage limits are violated, power system components, which are not designed to operate at voltages outside the predetermined range, can adopt undesired and unstable behaviour. Voltage limit violations are therefore avoided by the activation of protection actions which in severe cases can cause dynamic transitions which can lead to the following scenarios: [28, 30]

- the system adopts a new transient operating point within its region of attraction (the system is transient stable for that disturbance or event) and regains an equilibrium point which does not violate any operational security limit.
- the system adopts a new transient operating point within its region of attraction and regains an equilibrium point which violates at least one operational security limit.
- the system adopts a new transient operating point outside the system's region of attraction causing the operating point of the system to drift away until further protection actions take place or the system collapses.

Both thermal and voltage limits restrict the operational region of a power system. The restriction of the system due to operational security limits can be described by the following set of inequality equations:

$$\mathbf{l}^{\text{min}} \leq \boldsymbol{g}^{\text{res}}(\mathbf{p}) \leq \mathbf{l}^{\text{max}} \tag{2.4}$$

Here, $\mathbf{l}^{\text{min}}$ and $\mathbf{l}^{\text{min}}$ are vectors which describe maximum and minimum limits and $\mathbf{g}^{\text{res}}(\mathbf{p})$ is a non-linear function of the operating point $\mathbf{p}$.

Due to the discussed stability and operational security limits, a power system needs to be treated as a constrained dynamic system, since many of its quantities or functions of its quantities are required to remain within predefined regions to ensure a secure and stable behaviour of the system.[70]

2.2.4 Framework for the classification of power system operational states

From an operational point of view, the state of the system regarding its security of supply can be classified according to the framework provided by the Commission Regulation EU 20171485 [28]. Figure 2.4 gives an overview of the framework under consideration. The Framework comprises five classes which are briefly described in the following.

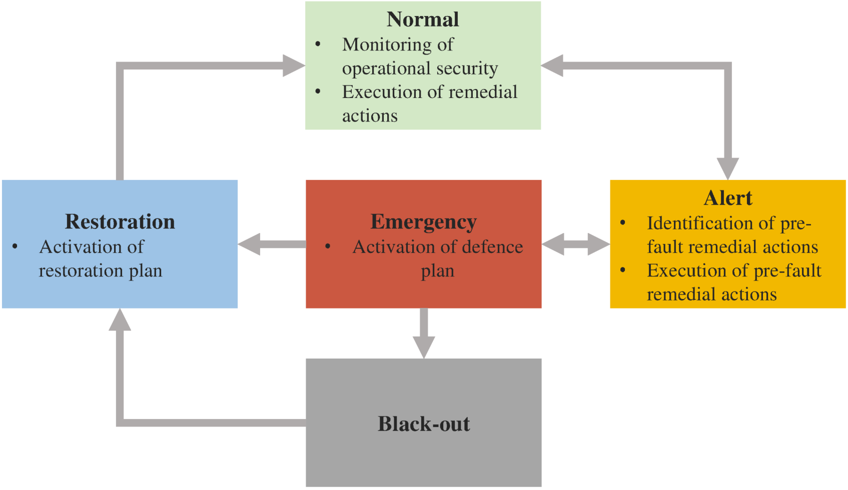


Figure 2.4: Framework for the classification of power system states according to [28] and [89]

Normal State: According to this classification, the system is considered to be in "normal state" when for a predetermined set of contingencies the system is considered to be safe in the sense of respecting operational security limits and its operating point is transient stable. An operating point is considered to be transient stable and safe for a predetermined set of contingencies when it can be expected that after any of the predetermined contingencies occur, the system will remain stable and the new operating point will not violate any operational security limit.

Alert State: The system is considered to be in the "alert state" when the operating point of the system is within its region of attraction and no operational security limit is violated but the occurrence of at least one contingency of the predetermined contingency list will either cause the operating point to leave the region of attraction or the violation of at least one operational security.

Emergency State: In case the operating point of the systems leaves the region of attraction and/or violates any operational security limit the system is considered to be in "emergency state".

Blackout State: If the operation of the complete or a part of the system is terminated (customer service is interrupted) the system is considered to be in "blackout state"

Restoration State: The system is considered to be in the restoration state when after the system has been in emergency or blackout state all activities are oriented to re-establish the normal operation state.

Power system operators are responsible for the security of supply of their corresponding responsibility areas and must, therefore, ensure that the system is most of the time in the normal state. Further, system operators need to ensure that in case unforeseen events or failures take place and the system leaves the normal state, a restoration of the operation of the system can be achieved by suitable measures (e.g. pre-fault remedial actions, defence actions or restorations actions).

Increasing the security of supply of a system is in general terms in conflict with the economic and technical efficiency which a system can achieve since increasing the security of supply is in general associated with

- investments in the power system infrastructure and in monitoring, control and protection schemes in the long term and
- non-optimal use of the available infrastructure to increase security margins in the short term.

However, system operators need to deal with this trade-off and attempt to find a suitable equilibrium between these two meta objectives.

In order to ensure that a power system can be operated in a secure and efficient way, several interventions are required. The next section gives an overview of the main interventions needed to be carried out to achieve these goals.

2.3 Operational interventions required for the operation of a power system

This section gives an overview of the main interventions which are essential for the secure and efficient operation of today's power systems. The selected interventions which are addressed below are classified according to their time scale. Fig. 2.5 gives an overview of the considered categories which were defined based on [89] and [64].

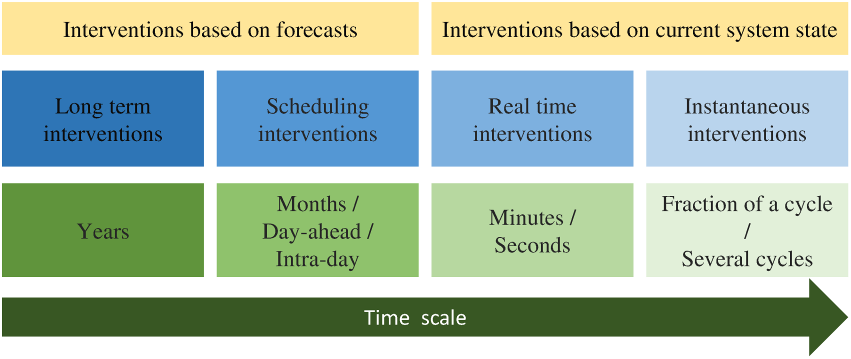


Figure 2.5: Classification of main interventions required for the operation of a power system

Instantaneous Interventions

A power system is constantly subject to external stimuli and as such, its state is constantly changing over time in a chaotic way. The capability of the system to cope with these stimuli is dependent on its ability to adapt itself to new situations without losing stability or violating operational security limits. To this, several instantaneous interventions are required, which have an impact on the operation of the system and are triggered almost instantaneously as soon as a relevant system state start to change. Thus, it can be said that instantaneous interventions are constantly influencing the state of the system. Thus, instantaneous interventions need to be carried out intrinsically by system components within a few cycles or even in a fraction of a cycle[1]. Instantaneous interventions result from intrinsic properties of system components following component

---

[1] One cycle at 50 Hz equals 1/50 s or 20 ms

design and natural laws or are enforced by control structures. Thus, they are automatic and do not require the action of humans. [64]

Instantaneous interventions are essential for maintaining the security of supply and the stability of the system in the instantaneous time scale. Instantaneous interventions are among others required for [52, 61]

- forming and regulating the frequency of the system
- forming and regulating the voltage of network buses
- protecting system equipment after the occurrence of failures.

An example of an instantaneous intervention which is enforced by a control structure is the regulation of the terminal voltage of a synchronous generator. If an external stimulus leads to a change in the voltage amplitude at a generator's terminal, the automatic voltage regulator starts adjusting the DC current supplied to the generator's field winding within a few cycles in order to maintain the terminal voltage at a predetermined value [52, 61].

An example of an instantaneous intervention which results due to the intrinsic properties of a system component is the inertial response of a synchronous generator. Due to their design, interface with the grid and physical properties, synchronous generators guarantee that abrupt changes in load are balanced within a fraction of a cycle adapting their active power output almost instantaneously [8, 61].

Real-Time Interventions

As stated above, the state of a power system is constantly changing due to external stimuli. In this context, power system operators have to continuously monitor and evaluate the state of the system and interfere when this is required to guarantee that the system is operated in an efficient, secure and stable manner. To this, several real-time interventions are required that act on a time scale of seconds to minutes. Real-time interventions need to be applied to ensure that the states of the system remain in a safe operating region where no operational security limits are violated and the stability of the system is not put at risk. [53, 60, 64]

The main difference between real-time and instantaneous interventions is the fact that the latter are carried out continuously as soon as a relevant state starts to change while the former are based on average values over periods of time or snapshots taken in fixed time intervals. Real-time interventions may take place automatically and be driven by ICT-Systems or they may depend on human decision-making and acting. Real-time interventions are e.g. required for [28, 30]

- corrective congestion management,
- system-wide balancing of generation and load,
- real-time optimization,
- system restoration after a black-out and
- maintenance purposes such as the isolation of lines or grid subsections.

Interventions related to the corrective congestion management are required for handling line overloads and voltage limit violations in real-time when the state of the system leaves a secure operating area. Interventions related to the corrective congestion management are for instance corrective re-dispatch actions in the transmission network, topology changes by switching of circuit breakers, deflection of load flows by changes on the behavior of phase-shifting transformers and voltage adjustments by tap changes of OLTC transformers. [28, 30]

Interventions related to the system-wide balancing of generation and load are required for ensuring that the power consumption within a control zone can be continuously supplied by the generation units within that zone or by the import/export of power with adjacent control zones. These interventions are e.g. actions related to the primary, secondary and tertiary frequency control, actions for corrections of deviations from import/export schedules among control areas or load shedding actions in emergency conditions according to a pre-established defence plan. [28, 30]

Interventions related to the optimization of the state of the network, are interventions which aim to change the operating point of the system such that the system is efficiently operated according to a pre-established goal. Such a goal can be of monetary, physical or another nature. The overall objective can be e.g. to supply the loads at minimum costs or to maintain transmission losses at a minimum. Interventions related to the optimization of the transmission and distribution networks are for example the real-time reduction of losses by re-dispatch actions, topology changes by switching actions, or the partial deflection of load flows by changes on the behavior of phase-shifting transformers. [28]

Interventions related to the restoration of the system after a total or partial black-out are measures which are required to initiate and establish the normal operation of the system after the complete or a part of the system has been terminated. These interventions are for example the actions related to the start-up or shut down of conventional power plants, actions required for the synchronization of islanded subsections of the grid or switching actions in transmission and distribution level for isolating and reconnecting grid subsections in a coordinated way. [28, 30]

Interventions related to maintenance purposes are actions which are required for the maintenance of grid components such as lines, generators, switching breakers etc. These are usually related to the controlled isolation of grid subsections without putting at risk or interrupting the operation of the remaining subsections of the system. These interventions include e.g re-dispatch actions to reduce component loading before isolation, switching of circuit breakers, etc.

Scheduling interventions

Instantaneous and real-time interventions are characterized by the need to maintain the stability and security of the system during or after a sudden change or fault occur. Scheduling interventions, on the other hand, are actions related to the ex-ante operational planning and optimization of the system (e.g. day-ahead and intra-day operational planning) and are based on forecasts.

Scheduling interventions are actions on the time scale of hours, days and months intended to achieve a secure and efficient operation of the system by ex-ante decision making. To this, the behavior of loads, distributed generators and other components is anticipated (forecasted) and based on this, generation schedules are determined and capacities allocated. The forecasts which are estimated in advance are subject to uncertainties that cause deviations of the schedules which need to be continuously managed by real-time and instantaneous interventions. Scheduling interventions are today mainly market-based and are supported by ICT-Systems but usually require human action and decision-making. [25, 26, 29]

Scheduling interventions include [25, 26, 29]

- actions related to the ex-ante market-based allocation (dispatch) of active power generation for specific time intervals through forward trading, day-ahead trading and intra-day trading.
- actions related to the preventive re-dispatch measures when violations of operation security limits can be anticipated.
- actions related to the ex-ante allocation of reactive power injection for voltage profile optimization and loss reduction
- actions related to the market-based allocation of balancing reserves such

as spinning reserves, reserve for primary frequency control, reserve for secondary frequency control and reserve for tertiary frequency control.

- actions related to the scheduling of control reserves for corrective remedial actions (e.g. corrective re-dispatch)

Long Term Interventions

In order to guarantee the security of supply in the long term, system operators need to ensure that the generation, transmission and distribution capacity is sufficient to supply the system loads in the long term and operate the system in a secure and stable manner. To this, long term interventions are required which are modifications of the system infrastructure such as the generation portfolio, the network topology, market design or operational principles according to long-time planning horizons based on a forecast of the supply task or expected changes in regulations or other external influencing factors. [1, 64, 89]

2.4 The role of conventional power plants in the operation of contemporary power system

In the previous section, interventions which today are essential for the secure and efficient operation of a power system have been discussed. These interventions are required to ensure a secure, stable and efficient system operation in the short term (Instantaneous and real-time interventions), plan and optimize the operation of the system in the mid term (Scheduling interventions) and guarantee the availability of generation and transmission capacities and reserves in the mid and long term (Long term interventions). Today, conventional power plants play a predominant role in all of these interventions. In the future, however, due to the decarbonization of the system, these plants will be replaced by a huge number of distributed generators. In this context, the following question arises: how will future power systems be operated when conventional power plants which are today essential for the interventions required for their efficient and secure operation are no longer in operation? In order to find an answer to this question, in this section, first, the role of conventional power plants in the interventions addressed in the previous section is discussed. Subsequently, the need for a new system architecture and operational concept aimed at enabling an efficient and secure future system operation in the absence of conventional power plants is addressed.

2.4.1 The role of conventional power plants in instantaneous and real-time interventions

Most instantaneous and real-time interventions currently required to ensure the stability and security of the system rely directly or indirectly on particular properties and capabilities of conventional power plants. [28, 54, 60].

Important capabilities which are essential for the performance of instantaneous and real-time interventions include for instance: [DM5]

- Inertial response capability
- Governor response capability
- Voltage enforcement capability
- Re-dispatch response capability
- Black-start capability

These capabilities are briefly described in the following[2]:

Inertial response capability: Conventional power plants use synchronous generators to convert mechanical into electrical power. The synchronous generators are driven by steam, gas or hydro turbines which provide the accelerating torque that produce the angular acceleration of their rotors which can be seen as energy storages. The rotating rotors induce an electromotive force in each phase of the armature winding of the stators which inject a three-phase alternating current into the power system. In this way, the rotational energy stored in the rotors is injected in the form of electrical power into the grid. The amount of electrical power injected at a given moment into the system by a particular synchronous generator is not directly dependent on the mechanical power provided by its prime mover. The electrical active power injected into the system is rather obtained from the rotational energy stored as kinetic energy in the rotor. Therefore, when the system load changes due to normal operational changes or due to a failure such as the tripping of a line or generation unit, the active power injected by a particular generator adjusts itself instantaneously according to the new load situation. Due to this physical property, conventional power plants continuously enforce, at short time scales, the power balance of active power consumption and active power injection in the system. This balancing service is inherently contributed by synchronous generators and is of fundamental importance to the stable operation of the system. [27, 52, 60]

---

[2] Some paragraphs or parts of paragraphs of this section have already been published in [DM5]. These passages were written to be published in this dissertation and were additionally included in [DM5].

Governor response capability: When the load situation in the power system changes, the electric power injected by the generators instantaneously adjusts itself (see inertial response capability). This causes an imbalance between the accelerating mechanical torque and the decelerating electrical torque acting on the rotors. The result is a deviation of the rotational speed of all the rotors of the system leading to frequency deviations. It is important to note here that a change of rotational speed can also be understood as a change in the amount of rotational energy stored which is available to dampen abrupt load changes. In order to ensure that the rotational speed of rotors – which is proportional to the system frequency – is kept within a pre-established and secure operating range, conventional power plants are equipped with turbine governing systems which are able to adjust the mechanical torque acting on the rotors. This property – the governor response capability – ensures that the energy stored in the rotors of synchronous generators is continuously replenished and the system frequency is kept at the rated frequency. The governor response capability of conventional power plants is a fundamental contribution to the stable operation of the system as it maintains the frequency within acceptable ranges even if the system load changes abruptly. [27, 52, 60]

Voltage enforcement capability: Conventional power plants are capable of regulating the voltage of their generator terminals according to reference values which are normally set by the transmission system operator. Through this, conventional power plants enforce a safe voltage situation near the substation they are connected to and thus make a substantial contribution to the stability of the system. Conventional power plants achieve this goal by means of their automatic voltage regulators (AVR). AVRs continuously monitor the voltage amplitude of the generator terminals and – based on a closed loop control structure – regulate the DC current supplied to the rotor field winding such that the amount of reactive power injected into the system is continuously adjusted to ensure an (almost) constant voltage amplitude at the generator terminals. It must be noted that the voltage reference value that the AVR uses as an input can be adjusted by the TSO when necessary in order to improve the overall voltage profile or influence the system state. [27, 52, 60]

Re-dispatch response capability: The node specific re-dispatch response capability, is the capability of a conventional power plant to adapt its active and/or reactive power output according to set points which can be directly (e.g. congestion management) or indirectly (e.g. voltage amplitude set points) determined by transmission system operators. In this context, it is important to consider that not only the flexibility of power plants to adjust their outputs is of interest, but particularly the fact that a system operator knows precisely where in the grid the injection change will take place if a power output adjustment for a particular conventional power plant is requested. This property is of crucial importance for the operability of the system, since, by means of the reference adjustments of active and reactive power injection at the nodal level, system operators can arbitrarily influence the state of the grid. In this manner, system operators can for instance (i) adjust power flows when lines are overloaded, (ii) influence the voltage profile of transmission buses to avoid voltage limit violations, (iii) reduce transmission losses or (iv) influence the exports and imports between control zones according to market conditions or international agreements. Due to these and other reasons, the re-dispatch response capability of conventional power plants is of crucial importance for the operation of the system which leads to the question of how these interventions will be applied in a scenario where the majority of conventional power plants have been decommissioned. [27]

Black-start capability and controllability for restoration purposes: When the operation of the system is interrupted due to an unforeseen event or failure, the normal operation of the system needs to be restored by a complex process where power plants and subsections of the system are initialized one by one, synchronized and reconnected. This process requires the involvement of personnel who coordinates the required measures to initialize the system [6]. In this context, the black-start capability and controllability of conventional power plants are of paramount importance. Power plants with black-start capability are able to re-energize a network subsection without a connection to an energized network (isolated bootstrap). Furthermore, these plants can be controlled to enable the synchronization and reconnection of network sections which have been re-energized individually and have dynamic properties which damp hazardous transients during the reconnection of isolated system subsections. Because of these important properties of conventional power plants, a collapsed power system can be successively restored until normal operation is achieved. [27]

The capabilities of conventional power plants discussed above are today essential for the operation of contemporary power system. As of today, even though conventional power plants are planned to be decommissioned in large scale in the next years, there is still no consensus of how these important properties will be substituted in the near future. However, a solution needs to be found in order to ensure the reliability of the system in the coming decades.

2.4.2 The role of conventional power plants in scheduling interventions

As stated in section 2.3, scheduling interventions are actions and decisions related to the operational planning of the system. These interventions aim among others at (i) ensuring the optimal use of the transmission infrastructure, (ii) ensuring its operational security and stability (iii) ensuring an optimal use of generation and transmission capacities and (iv) promoting effective competition in the generation, trading and supply of electricity [25, 26, 29]. As of today, operational planning tasks are highly related to the market-based scheduling of conventional power plants. In this context, after determining by a market-driven process which conventional power plants will contribute in what extend to the power generation required to supply the loads, a set of preventive measures are taken in order to enable that the market result can be realized in such a way that the associated system state is stable, do not violate any operational constraints and can be classified as normal according to the framework for security classification presented in section 2.2.4. To this, based on the market-based schedules of conventional power plants, TSOs e.g. need to anticipate expected network losses and contract generation capacities to ensure that the active power in the system is balanced. Furthermore, in case security risks associated with the market-based generation schedules are identified, preventive grid- or market-related measures in the scope of congestion management need to be taken. This includes, for example, preventive redispatch actions and power-feed-in adjustments by counter trading. [25, 26, 29]

All these activities (the market-based allocation of generation schedules and the planning of preventive measures to ensure that the market result can be realized without endangering the security of the system) rely, among others, on the fact that currently, market participants and system operators have access to information regarding the "flexibility range" of conventional power plants. Here, the flexibility range refers to the range in which conventional power plants are able to inject active and reactive power into the system which is described by their capability curves. The flexibility of conventional power plants to adapt their active and reactive power behavior is constant over time. This property is essential for the way scheduling interventions are conducted today and can be seen as the foundation for the operational planning of contemporary systems.

In future, however, under the assumption that conventional power plants will be decommissioned, the scheduling interventions which are performed today will need to be fundamentally reviewed. In particular, because the operational flexibility of renewable energy sources varies over time and is subject to uncertainty. Up to now, however, there is no consensus with regard to how scheduling interventions will be organized and carried out in future, in particular when the majority of the power generated in the system is provided by renewable energy sources and only very few conventional power plants are still in operation.

2.4.3 The role of conventional power plants in long term interventions

In the long term, power system operators need to ensure that the power system infrastructure is able to cope with the long term electric power supply task. To this, long term forecasts need to be done in order to anticipate how the load distribution will change and to determine if the available generation and transmission capacities will be sufficient. In case capacity shortages are identified, the system infrastructure needs to be extended to protect the future security of supply. [32] In this context, conventional power plants play a predominate role since one of the main tasks in the context of long term planning lies in assessing if the available (mainly conventional) generation capacities will be sufficient to supply the system load and if the transmission capacities will be adequate. Based on this analysis, the required extensions of generation and transmission capacities can be determined. [1]

In a scenario where conventional power plants have been extensively replaced by distributed generators, the long term planning and the interventions required need to be fundamentally reviewed and modified. As of today, there is no consensus in regard to how a power system will be planned in the long term without considering conventional power plants.

2.5 The need for a new power system architecture and operational concept

The decarbonization goals currently being pursued worldwide have resulted in important incentives for the large-scale system integration of generators based on renewable energy sources [76]. These efforts can so far be considered successful if the increase in the share of renewable energies in gross electricity generation is taken into account [76]. However, on closer examination, it becomes evident that this development also has significant shortcomings, particularly concerning the future operability of the system. Up to now, most of the efforts to establish guidelines and regulations for the integration of renewable energies have been undertaken under the assumption that the fundamental operational principles of contemporary power systems will remain valid in the future. The main focus of the current regulatory framework is, therefore, to integrate renewable generation sources avoiding a negative impact on the current operation of the grid. However, the regulations do not foresee how the system will be operated in the long term when the majority of conventional power plants have been replaced by a large number of decentralised generator units connected mainly at the distribution network level [28]. This can be seen as a problem since the way renewables are being integrated today actually implies extra stress for the operation of the transmission network. As a consequence, if the number of renewables continues to increase without a drastic change in how the system is structured and operated, the system will become non-manageable and the risk of instability will increase.

In order to solve this problem and be able to further increase the share of renewable energies in the future, it is crucial to anticipate how the interventions necessary for the operation of the system, which currently depend on conventional power plants, can be substituted. To this end, it is necessary to revise the structure, control and operation of the system and to develop a new system architecture with new operating paradigms that are able to accommodate a high number of distributed generation units in all voltage levels while the operability of the wide-area system remains feasible.

Chapter 3 addresses this problem by describing a system architecture and operational concept for the cross voltage level operation of future power systems. The concept aims to integrate distributed generators, storages, flexible loads and multimodal interfaces connected at the distribution network level on the operation of the entire system by providing a framework for TSO-DSO coordination. The developed architecture and operational concept have been developed under consideration of the progress which has resulted from contemporary research in the area of TSO-DSO coordination and is intended to unify a series of developments into one comprehensive and holistic vision. By this, the concept aims to be a framework for further developments for ensuring the efficiency, security and stability of future power systems. In the next section, an overview of contemporary literature addressing solutions for the problems previously discussed is provided.

2.6 Literature review on TSO-DSO coordination and research gap analysis

The need for understanding and managing TSO-DSO interactions to enforce the security, stability and efficiency of future power systems has rapidly gained attention in recent times. The ENTSO-E, for instance, has already addressed this issue and recommends to enforce the cooperation of TSOs and DSOs to cope with the challenges arising from the large scale integration of distributed and renewable energy resources and the decommission of conventional power plants [20, 21, 22]. Further, several research initiatives are currently focusing on advanced TSO-DSO cooperation. This, for instance, has been reported in [44] where an overview of the main research scopes and trends of current projects is provided. Moreover, as of today, several countries around the world have implemented simple procedures for coordinating TSO-DSO interactions and this trend is expected to continue [99].

The increasing interest in TSO-DSO coordination is also reflected in many recent publications which suggest several methodologies and schemes to engage distribution networks in the provision of ancillary services at transmission level. For example, in [5, 11, 75, 94, 100] the focus is set on exploring how distribution networks can participate in the regulation of transmission voltages, by means of suitable control schemes. In [57, 104] the relief of congestions at transmission network level by the suitable control of distribution networks is discussed and approaches for that purpose are suggested. Furthermore, methodologies for the participation of distribution networks on the provision of balancing services and frequency control has been discussed e.g. in [38, 77].

Other contributions address the TSO-DSO coordination problem in a more general way focussing on controlling the apparent power that distribution networks exchange with the transmission grid. Note that this power flow will in the following be referred to as Interconnection Power Flow (IPF) [3]. Focussing on the IPF is mainly motivated by two ideas: (i) the interaction of a distribution network with a transmission network at a given moment can be described by its corresponding IPF and (ii) several services which a distribution network can provide to a transmission network can be induced by adjusting its IPF. Methodologies to control the reactive IPF have been proposed in [12, 50, 62, 68, 81, 84, 96]. On the other hand, methodologies and schemes to control the active IPF are suggested for instance in [9, 80, 83, 85, DM19]. Surprisingly, only few contributions [24, DM12, DM14, 86] focus on the simultaneous control of both, active and reactive

---

[3] see also definition 2 in section 3.7

IPF. This, however, is of paramount importance since changes in the active and reactive power behaviour of a distribution network are highly interrelated and therefore a simultaneous control is required [DM12].

Distribution networks can only adjust their IPFs to a restricted extent depending on several limiting factors. Therefore, the scope of many recent publications is set on characterizing the flexibility of a distribution network to adjust its IPF. A methodology for the characterization of the flexibility of a distribution grid to adjust its active IPF is e.g. discussed in [58]. On the other hand, methodologies for determining the flexibility of a distribution network to adjust its reactive IPF are discussed in [35, 37]. The characterization of the flexibility of a distribution network to adjust both, its active and reactive IPF is addressed in [10, 14, 31, 42, DM10, 88]. While in [10, 14, 31, 88] the flexibility is determined based on optimization, in [42, DM10] a Monte-Carlo approach is used. In particular, in [DM10] it is shown that the flexibility of a distribution network to adjust its IPF varies over time and that a flexibility forecast is subject to uncertainty.

Despite the important contributions related to the coordinated operation of distribution and transmission systems mentioned above, there is still a need to tackle the TSO-DSO coordination problem following a holistic approach, in particular when scenarios with a very high penetration of distributed generators and very low shares of conventional power plants are taken into account. In this context, distribution networks will not only be expected to support the operation of the system as an additional source of flexibility but will, in fact, become the foundation of the operability and stability of the system. To this end, the control schemes implemented within distribution networks will need to be able to coordinate their behaviour in such a way that all services required for the operation of the system can be provided simultaneously, even if no conventional power plants are in operation. This is a very challenging undertaking since many of the services required can lead to conflicting control targets and inconsistent system behaviour, in particular when they are simultaneously provided by distributed resources connected at distribution network level. This becomes clear with some examples:

- Controlling the active or reactive IPF of a distribution network for congestion management or voltage support at transmission level can lead to voltage limit violations or congestions at distribution level,
- controlling the IPFs of several distribution networks simultaneously can have a critical impact on the overall active power balance of the system and cause frequency fluctuation,

- virtual inertia and local voltage control at distribution network level has an impact on the IPFs which can lead to conflicts with control instructions provided by a superimposed monitoring and control system which e.g. requests to adjust IPFs for congestion management or system optimization.

In this light, it is evident that the development of control structures and coordination schemes to enable the participation of distribution networks in the operation of the transmission systems requires a holistic approach. In particular, the suitable performance of the implemented control schemes when several services are provided simultaneously need to be verified and enforced. In this context, studying the provision of single services by distribution networks assuming that the current system's architecture and all remaining operating principles will remain unchanged seems to be insufficient. Instead, this dissertation assumes that the operational principles of future power systems need to be holistically revised and a new system architecture needs to ve developed. In particular, due to the displacement of controllable resources able to provide ancillary services from the transmission to the distribution level, distribution networks should be perceived as intelligent and controllable entities which are require to meet predetermined requirements regarding their dynamic behaviour and controllability in order to operate in a secure and stable way and at the same time integrally support the operation of the system. A similar idea has been discussed in [74] were the aggregation of distributed resources within a distribution network to form a so- called "technical virtual power plant", which is a controllable entity with similar properties to those of conventional power plants, has been proposed. In [74] however, only an abstract description of such a virtual power plant is given and concrete control objectives for the monitoring and control system of such a system are missing. To close this gap, in this dissertation, a new power system architecture and operational concept are introduced in section 3. The core element of the proposed architecture is a "Smart Power Cell" which can be seen as an extension of the "technical virtual power plant" proposed in [74]. Here, it should be noted that the term "virtual power plant" is not used in the following since several publications (see e.g. [78]) use the same term to refer to very different concepts which are little related to the "technical virtual power plant" concept explained in [74].

2.7 Summary

In the previous sections, an overview of the operation principles of contemporary power systems is provided. In addition, the main interventions which are required to operate current systems in a secure, stable and efficient way are addressed. Later on, the importance of conventional power plants for the identified interventions is discussed. By this, it is shown that the operability and security of today's system are mainly built upon the capabilities and properties of conventional power plants. Based on this analysis, the need for restructuring the way the system is organized and operated is postulated. This need is justified by the plans to decommission a major part of the conventional power plants currently in operation in the next decades. Finally, an overview of the state of the art approaches intended to find solutions for specific challenges resulting due to the decommissioning of conventional power plants is given. In particular, the addressed approaches suggest methods to operate transmission and distribution grids in a coordinated way and by this integrate generators, storages and flexible loads connected at all voltage levels in the operation of the system. The discussed approaches, however, focus on specific problems and do not provide a holistic solution for the future operation of a power system. This dissertation is intended to close this gap and suggests a new system architecture and operational paradigm to integrate the operation of transmission and distribution grids and by this ensure the secure, stable and efficient operation of future power systems. The system architecture and the operational concept which were developed to close this gap are described in the next chapter.

3 The Smart Power Cell Concept

In the previous chapter, an overview of the structure and operation principles of contemporary power systems has been given. Subsequently, the chapter addressed operational interventions which are essential for the operation of the system and discussed the role which conventional power plants play in this context. In the end, the chapter explained that the way distributed generators are currently being integrated is based on the assumption that the main operating principles of the system will remain unchanged in the future. This assumption, however, is not admissible since the conventional power plants, which are planned to be decommissioned in the next decades, are today the foundation of the operability and stability of the system. This pseudo substitution of conventional power plants by huge numbers of distributed generators mainly connected at the distribution network level is speeding up, even though, it is still not clear how a future power system with very high shares of renewables can be operated in a secure and stable way. It is in this context of dramatic and fast changes that answering the following question becomes a matter of urgency:

> How will the power system of the future be planned and operated so that its efficiency, security and stability can continue to be guaranteed when most conventional power plants - which today are the foundation for the operability and stability of the system - will no longer be in operation?

As a contribution to answering this question, this chapter is devoted to describe an architecture and operational concept which is later used as an envelope for the methods presented in this thesis. The main objective of the concept is to enable the efficient, secure and stable operation of a future power system with a very high penetration of distributed generation.

Note that preliminary descriptions of the architecture and the concept suggested in this chapter have been published in previous work [DM5, DM9, DM10, DM12, DM13].

The chapter is structured as follows. Section 3.1 gives an overview of the developed architecture and describes its core element: The Smart Power Cell (SPC). Then, in section 3.2 and section 3.3, components of SPCs and their properties are described. Note that, in this two section, some fundamentals are reviewed and terms are introduced, which are required to understand the developed concept but are considered to be basic knowledge in the field of power system engineering. Subsequently, in section 3.4 the main objectives of the monitoring and control system of an SPC are described. In section 3.5 and 3.6 the required measurement equipment and communication infrastructure is briefly addressed. Next, the interface between an SPC and the transmission network is described in section 3.7. In particular, in this section, important terms are introduced which are required to understand the methods presented in chapter 5 and 6. Then, section 3.8 deals with the fact that an SPC is a dynamic system and briefly describes how its dynamic behaviour can be studied and represented. As SPCs are intended to be integrated in the operation of a future power system, in section 3.9 a cross voltage level coordination concept is provided. The coordination concept describes how a future power system composed of a transmission network and several SPC could be monitored and operated. Finally, the chapter closes with section 3.10 discussing the future role of SPCs in the operation of a power system.

3.1 Overview of the developed system architecture

The developed architecture for the operation of future low emission power systems is founded on the idea of reorganizing the distribution network level in supervised and controlled grid subsections called Smart Power Cells (SPCs). SPCs are intended to enable the coordinated operation of sets of interconnected generators, loads, storages and multimodal interfaces in such a way that each set of components belonging to a particular SPC is perceived by the transmission system operator as a single controllable entity with a specific, known and adaptable dynamic behaviour. By this, the TSO can supervise the behaviour of the components of an SPCs only taking aggregated information into account. Furthermore, in case of need, a TSO can issue aggregated control instructions to adjust the behaviour of SPCs when this is required to ensure the efficient, secure, and stable operation of the system.

By means of this architecture, the interventions which are required to operate the system and today rely on the capabilities and properties of conventional power plants can be substituted. To this, SPCs need to be designed, planned and operated in such a way that their behaviour enforces the stability of the entire system. Furthermore, by means of a suitable monitoring and control, SPCs need to be able to adapt their behaviour in real-time such that they can participate in the operation of the transmission network when this is required due to efficiency or security reasons.

The developed architecture seeks, therefore, to guarantee the operability and stability of a future power system with a very high share of distributed and renewable generation and a low number of conventional power plants in operation.

A schematic overview of the fundamental structure of a future power system organized according to the SPC concept is depicted in Fig. 3.1. The illustrated system is composed of several SPCs (green boxes) connected to a transmission network (grey box) which is only partially illustrated. In Figure 3.1, only the SPC with index $n = 1$ (green box below) is depicted in detail, but it is assumed that the remaining SPCs have a similar structure.

Each SPC is composed of a set of distributed generators, loads, storages and multimodal interfaces[4] interconnected by a three-phase AC grid. Within an SPC electric power is generated, distributed and consumed while the mismatch between generation and consumption within the cell is balanced by the coordinated power exchange via its interface with the transmission network. The behaviour of an SPC is continuously supervised and controlled by a monitoring and control system which guarantees that the security and stability of the cell are continuously given and that the cell behaves in a supportive way with regard to the security and stability of the transmission grid. Thus, an SPC can be seen as a controllable entity which is able to flexibly adapt its dynamic behaviour as well as its power consumption or generation in order to interact with the transmission network via its interface in a regulated and supportive way. To this, each SPC is interfaced with the transmission network by means of an OLTC transformer which interconnects a particular transmission network bus with a particular SPC bus. These OLTC transformers embody the interface between transmission and distribution domain and enable the active and reactive power exchange between domains. The high voltage side terminal of the OLTC transformer is considered to be the interconnection bus which delimits the transmission and distribution domain. As illustrated in Fig. 3.1, it should also be noted, that each SPC can comprise several voltage levels interconnected by transformers. In the illustrated example, SPC 1 comprises one medium voltage grid and two low voltage networks. The medium voltage grid is composed of three medium voltage buses and two medium voltage lines. Both low voltage networks are connected to buses of the medium voltage networks via OLTC transformers: The low voltage network (a) is connected to bus MV-2 and the low voltage network (b), which is not illustrated in detail, is connected to the medium voltage bus MV-3. Here it is important to note that this is only an exemplary topology. In general, the SPC concept can be applied to a wide variety of grids with very diverse topologies.

---

[4] Multimodal interfaces are intersections with other energy carrier networks such as gas and heat grids. These interfaces enable controlled power flow from the electric system into another energy carrier network and vice versa.

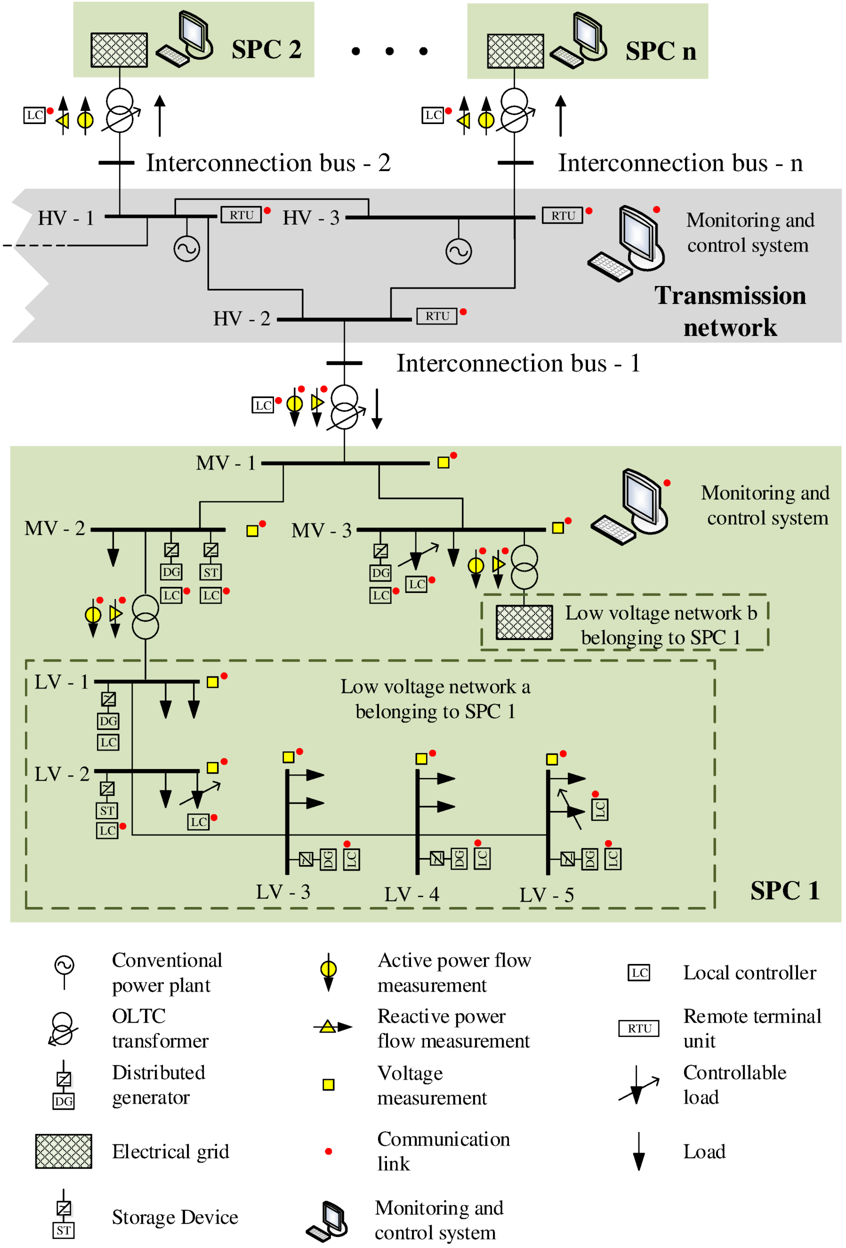


Figure 3.1: Schematic overview of the fundamental structure of a future power system organized following the SPC concept

3.2 Power Conversion Units within a Smart Power Cell

As stated above an SPC is a subsystem composed of a set of generators, loads, storages and multimodal interfaces interconnected via an AC three-phase electric grid. These components interact with each other via the grid and determine how an SPC behaves. In this section, the description of the behaviour of these components with regard to the behaviour of an SPC is addressed. For simplicity's sake, in order to refer to all these components simultaneously, henceforth the term Power Conversion Units following definition 1 is used:

Definition 1 (Power Conversion Unit - PCU)**.** *A power conversion unit is a component of the power system that converts energy from one of its forms (e.g. mechanical, thermal, chemical) into electric energy or vice versa by capturing energy from one system and releasing it into another system by means of a power flow. A power conversion unit has always a well-defined interface with the electric system by which the power exchange with the electric grid takes place. Note that the expression does not make any distinction between the power flow direction of the unit. Thus, according to this definition any load, generator, storage or multimodal interface can be referred to as a power conversion unit.*

A Power Conversion Unit (PCU) interacts with the grid via its interconnection point which is the bus bar the PCU is connected with. The most common connection types to interface a PCU with a busbar are:

- Single-phase, line-to-line connection,
- single-phase, line-to-neutral connection,
- three-phase, delta connection and
- three-phase, wye connection.

PCUs interact with the grid by means of a current which is absorbed from or injected into the busbar the units are connected with. Thus, the impact of a PCU on an SPC can be modelled using controlled current sources which map the current absorbed or injected by the unit. Fig. 3.2 gives an overview of the most common connection configurations which can be applied to interface a PCU. Note that the interfaces of PCUs with their connection points are represented here by current sources.

All four types of connections are relevant in the SPC context and therefore the impact of the different configurations needs to be taken into account when SPCs are analysed and designed. In this thesis however, only three-phase connected PCU are considered and it is assumed that the system is operated under balanced

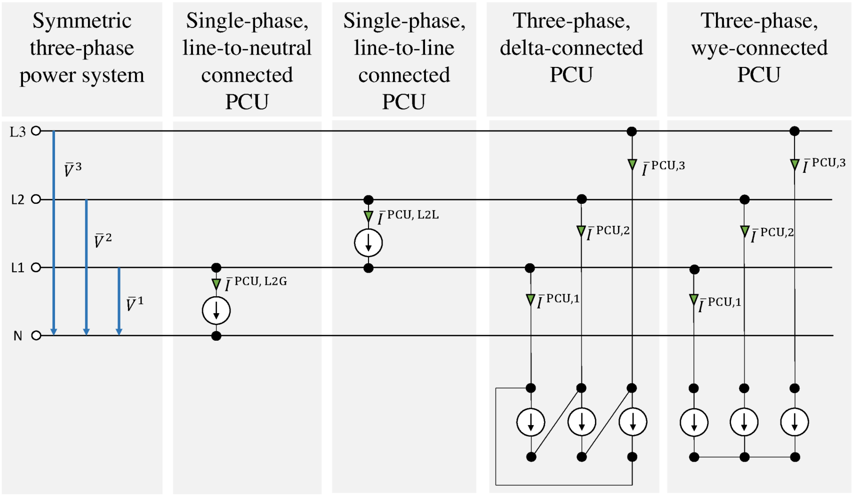


Figure 3.2: Overview of common interfaces of PCUs modelled with controlled current sources

three-phase positive sequence conditions. Taking this assumption into account, both three-phase delta-connected and three-phase wye-connected PCUs can be represented by a single-phase equivalent model as Fig. 3.3 shows. Henceforth, if not stated otherwise, all electrical explanations regarding the behaviour of SPCs and their components will be done under the assumption of symmetric operation using single-phase representations. The description of the behaviour of an SPC and their components under consideration of non-symmetrical operation is not addressed in detail here and will need to be covered in future work.

Under the assumptions introduced above, the behaviour of a three-phase connected PCU can be described with the equivalent circuit depicted in the left side of Fig. 3.4. The state of the busbar a PCU is connected with can be described by the complex voltage $\bar{V}^{\mathrm{CP}}$. The interaction of the PCU with the grid can be described by the current $\bar{I}^{\mathrm{PCU}}$ which is the current that the PCU absorbs from or injects into the grid via its connection point. The apparent power behaviour $\bar{S}^{\mathrm{PCU}}$ of the PCU results from these quantities and can be expressed by

$$\bar{S}^{\mathrm{PCU}} = P^{\mathrm{PCU}} + jQ^{\mathrm{PCU}} = 3\bar{V}^{\mathrm{CP}}(\bar{I}^{\mathrm{PCU}})^*. \tag{3.1}$$

The apparent power behaviour $\bar{S}^{\mathrm{PCU}}$ of a PCU can be graphically represented as a vector or a point in the P/Q plane as the right side of Fig. 3.4 shows. The

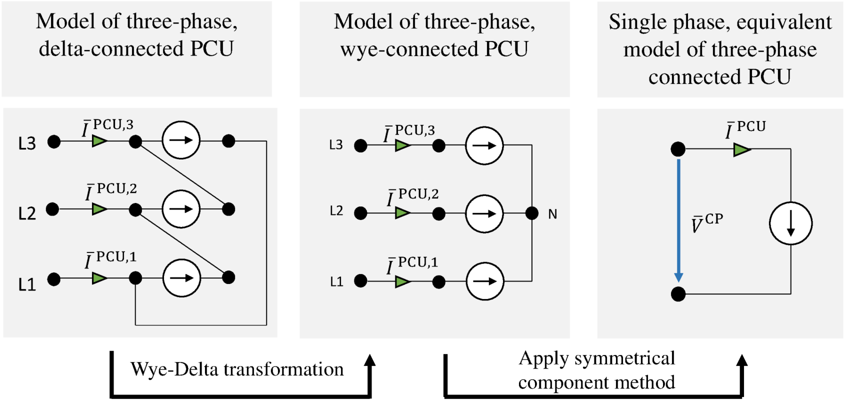


Figure 3.3: Single phase representation of a three phase connected Power Conversion Unit operating under three-phase positive-sequence conditions

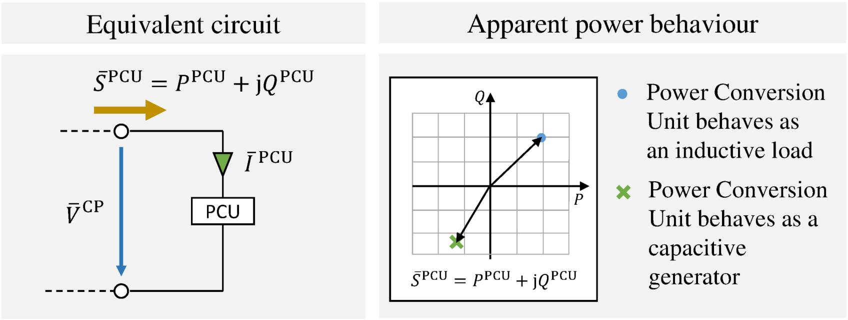


Figure 3.4: Description of the interaction of a Power Conversion Unit with the grid

right side of the Fig. 3.4 depicts two exemplary operating points. The blue dot ($P^{\mathrm{PCU}} \geq 0$ and $Q^{\mathrm{PCU}} \geq 0$) is an example of the apparent power behaviour of a PCU which behaves as an inductive load. In this case, this exemplary PCU absorbs active and reactive power from its connection point. The green cross ($P^{\mathrm{PCU}} \leq 0$ and $Q^{\mathrm{PCU}} \leq 0$) is an example of the apparent power behaviour of a PCU which behaves as a capacitive generator. In this case, this exemplary PCU injects active and reactive power into the grid.

PCUs can be classified according to whether they are controllable or not:

Non Controllable Power Conversion Unit (NPCU) NPCUs are PCUs whose behaviour depend on the voltage of their connection points and additional external influencing factors which are generally subject to uncertainty and cannot be influenced by the system operator. Thus, NPCUs cannot be controlled and have a random behaviour. This random behaviour has an impact on the behaviour of an SPC which SPC operators need to manage. To this, SPC operators can rely on probabilistic methods to anticipate the behaviour of NPCUs. However, probabilistic methods are by nature subject to uncertainty and therefore, when an SPC needs to adopt a particular behaviour in order to support the operation of the transmission system, the monitoring and control system of the SPC needs to counteract changes on the behaviour of NPCUs by control measures. Examples for non-controllable PCUs are conventional loads or PV-units operated at the maximum power point.

Controllable Power Conversion Unit (CPCU) CPCUs are PCUs whose behaviour can be controlled by a superimposed control system such as the monitoring and control system of an SPC. The behaviour and flexibility of these units are in general terms also dependent on external influencing factors but their operating point can be adjusted within a determined range such that their interaction with the grid can be controlled according to the overall control objectives of an SPC. Examples for controllable power conversion units are flexible loads or PV-units equipped with an appropriate communication interface and control structure for being operated according to set points issued by a superimposed control system.

Both CPCUs and NPCUs are dynamic systems whose operating points and therefore also the way they interact with the grid vary over time depending on their current state and external influencing factors. Such dynamic systems can be mathematically modelled using differential-algebraic equations. The resulting set of equations describes how the states and the output signals of the modelled systems evolve over time depending on the trajectories of the input signals, which model the factors which influence the behaviour of the system. In practical terms, this means that the current which is injected into or absorbed from a busbar of an SPC by a PCU is determined by the dynamic behaviour of the PCU and the signals which have an impact on it.

A high-level representation of the models which can be used to describe the behaviour of a PCU is given by Fig. 3.5 and Fig. 3.6.

As the figures show, both the behaviour of CPCUs and NPCUs depends on the complex voltage $\bar{V}^{\mathrm{CP}}$, which is the voltage of the busbars they are connected

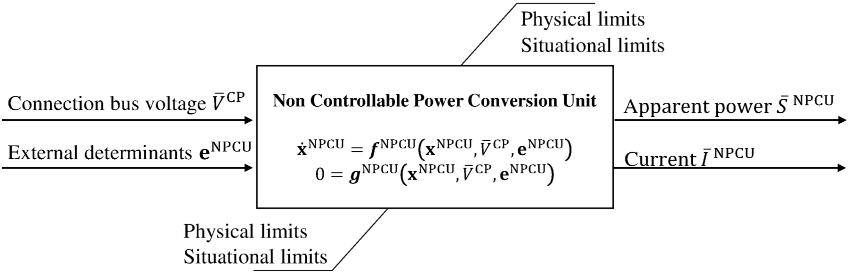


Figure 3.5: High level representation of a model to describe the dynamic behaviour of a non-controllable power conversion unit

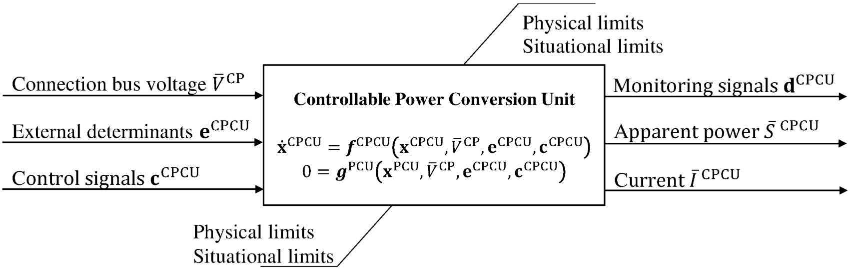


Figure 3.6: High level representation of a model to describe the dynamic behaviour of a controllable power conversion unit

with. This means, that in case the voltage of the busbar to which a PCU is connected changes, this also has an influence on the outputs of the unit and therefore on the way these units interact with the SPC.

In addition, the figures also show that the behaviour of CPCUs and NPCUs depends on a set of external determinants which are mapped by the vectors $\mathbf{e}^{\mathrm{CPCU}}$ and $\mathbf{e}^{\mathrm{NPCU}}$. These vectors describe the trajectories of external signals which have an impact on the modelled PCUs. Which signals are mapped by the vectors $\mathbf{e}^{\mathrm{CPCU}}$ and $\mathbf{e}^{\mathrm{NPCU}}$ depends on the modelled systems and the degree of detail chosen to model them. For example, if a non-controllable photovoltaic unit is modelled, the vector $\mathbf{e}^{\mathrm{NPCU}}$ would include elements which map the evolution of the solar radiation and temperature over time. In case a wind energy converter is modelled, the vector $\mathbf{e}^{\mathrm{NPCU}}$ would need to map the evolution of the wind speed acting on the rotor of the wind energy converter. Furthermore, for the modelling of an industry load, the external determinant vector $\mathbf{e}^{\mathrm{NPCU}}$ could include e.g.

signals describing the current production output of a production plant.

The main difference between a CPCU and a NPCU is that the behaviour of a CPCU can be influenced by signals mapped by the control vector $\mathbf{c}^{\mathrm{CPCU}}$. These signals can be issued by a local controller or a superimposed monitoring and control system. In this way, a PCU can receive set points which the unit needs to track in order to influence the behaviour of the SPC. However, it should be noted that the behaviour of a CPCU cannot be fully controlled, since its control signals only specify a desired behaviour which not always can be fulfilled. This is, for example the case when a behaviour is requested which would damage the equipment or could lead to an unstable behaviour of the system. To avoid this, PCUs are equipped with protection mechanisms and control structures which are designed to avoid that the operation of the unit violates predetermined limits. Some of these limits are time-invariant and don't depend on external influencing factors. Other limits change depending on the environment and therefore are time-variant. When a behaviour is requested by mean of control signals which would violate any of these pre-established limits, the unit would not track these set points leading to a discrepancy between the requested and realized behaviour. An example of a time-invariant limit can be found in the control structures of converters of PV-units, whose control systems include a current limiter to prevent damages caused by thermal losses. Due to this limitation of the current which a converter can inject into the system, also the apparent power which the unit can inject into the grid is bounded. An example of a time-variant limit is e.g. a limit which changes depending on an influencing factor. A concrete example for such a limit would be an active power injection limitation which would adjust itself depending on the frequency of the system.

Another reason which explains why a CPCU could not behave as required by the control signals is its dependency on the input of the system on other influencing factors. A PV-unit, for example, which is operated at night will not be able of increasing its active power output regardless if it is requested to do so by its control signals since its potential to inject active power is also dependent on the solar radiation in the moment of operation.

Furthermore, also in the short term, deviations from the desired behaviour are possible due to transitional events. Whenever input signals abruptly change, PCUs initially adopt a transient state which leads to a dynamic transition which persists until the desired stable operating point is achieved. During these dynamic transitions, deviations from the requested behaviour are possible, even though no limits are reached and the input signals enable the unit to behave as requested by the control signals.

In summary: The behaviour of both CPCUs and NPCUs depend on external influencing factors which are subject to uncertainty and cannot be influenced by the system operator. The behaviour of CPCUs, however, can be influenced to a certain extent by control signals.

When the behaviour of a PCU is described retrospectively, the interaction of the unit with the grid can be described by the trajectory of its outputs. A condensed way to describe the behaviour of a PCU is by the trajectories of its apparent power behaviour. Fig. 3.7 shows an exemplary trajectory of the apparent power exchanged by an exemplary PCU. In this case, the trajectories depicted correspond to a PCU which behaves as a conventional load.

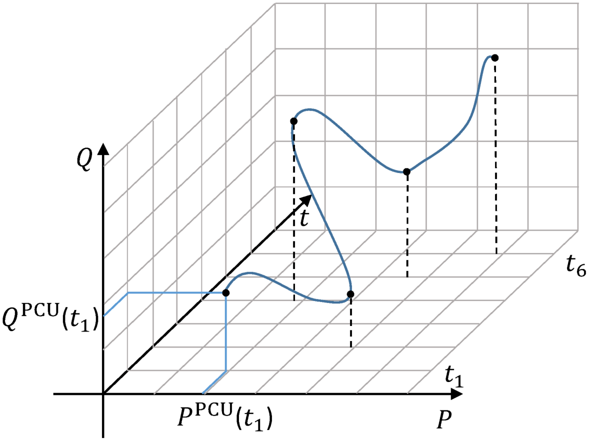


Figure 3.7: Exemplary trajectory of the active and reactive power behavior of a Power Conversion Unit

3.3 Components involved in the transmission of electric power within a Smart Power Cell

PCUs interact with the electric grid of an SPC by injecting or absorbing a current into the busbars they are connected with. The sum of currents which flows into a busbar is at all times equal to the sum of currents which flows out of that busbar. The deviation between the current injected into and absorbed from a particular busbar i by the PCUs connected to it can be expressed by

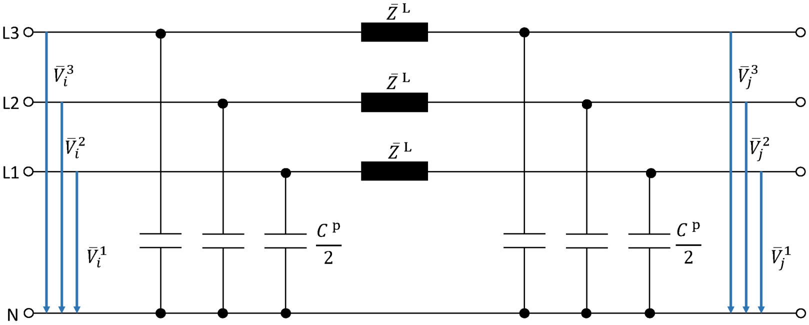


Figure 3.8: Three-phase equivalent circuit used to represent, describe and model three phase electric lines and cables

$$\bar{I}_i^{\mathrm{N}} = \sum_{p \in P_i} \bar{I}_p^{\mathrm{PCU}}. \tag{3.2}$$

$\bar{I}_i^{\mathrm{N}}$ is also known as the nodal current of node i and is the sum of the currents of all PCUs $p \in P_i$. Here, P_i is the set of PCUs connected to the busbar i.

The same applies for the apparent power balance of a busbar. The total apparent power which flows into a particular busbar at any given time is equal to the total apparent power which flows out of that particular busbar at that moment. The gap between the apparent power injected into and absorbed from a busbar i by the PCUs connected to it can be expressed by

$$\bar{S}_i^{\mathrm{N}} = \sum_{p \in P_i} \bar{S}_p^{PCU}. \tag{3.3}$$

Both the nodal current $\bar{I}_i^{\mathrm{N}}$ and the nodal apparent power $\bar{S}_i^{\mathrm{N}}$ of a bus i need to be offset by current and power flows over the lines which connect the bus i with other buses of the SPC. This leads to current and power flows over the lines and cables which interconnect the busbars which belong to an SPC. The cables, lines and busbars together with additional equipment such as transformers and circuit breakers form the electric grid of an SPC. The electric grid enables the interaction of PCUs among themselves and also the interaction of the complete SPC with the transmission network. The electric properties and the behaviour of a three-phase line can be described by the three-phase equivalent circuit depicted in figure 3.8. The simplified single-phase representation of a three-phase

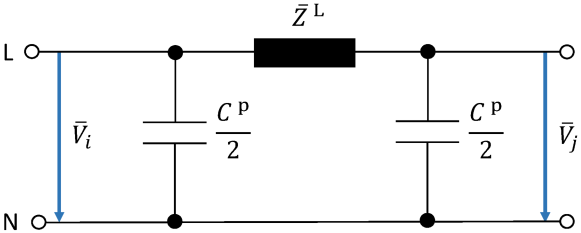


Figure 3.9: Single-phase equivalent circuit used to represent, describe and model three phase electric lines and cables under balanced, three-phase positive sequence conditions

line which can be considered under balanced, three-phase positive sequence conditions is depicted in figure 3.9.

The state of the electric grid of an SPC at a given moment can be described by the voltages of its busbars. Assuming steady-state conditions, these voltages can be determined by a load flow analysis, as is discussed in section 4. Other quantities (e.g. line currents and power flows), which need to be considered when the operation of the grid is analysed, can be derived once the voltages of the grid are known using the equivalent circuit depicted in figure 3.8 or in figure 3.9 (see section 4).

The operator of an SPC has several options to influence its electric state. A direct way, which has already been discussed above, is changing the nodal currents of the grid by adjusting the active and reactive power behaviour of PCUs. These changes, however, also have an impact on the voltage profile as well as on the current and power flows over the lines of the SPC. Thus, changes in the behaviour of PCUs can only be done under consideration of restrictions to avoid that the operation of the system is put at risk.

Another way to have an impact on the state of an SPC is to change the topology and electrical properties of its electric grid by changing the state of discrete switching devices such as circuit breakers or OLTC transformers. Changes of this type, however, have an impact on the state of an SPC and thus can only be conducted under consideration of restrictions to avoid that the operation of the system is put at risk.

3.4 Objectives of the monitoring and control system of a Smart Power Cell

The main objective of the SPC concept is to bundle PCUs at the distribution network level in SPCs such that a transmission system operator does not need to deal with the behaviour of single PCUs or consider how single PCUs impact the behaviour of the grid. Instead, the concept seeks to enable transmission system operators to interact with SPCs assuming that they are monitored and controlled entities which are able to adapt their behaviour in order to support the operation of the transmission network without the need of considering SPC-internal feasibility, efficiency, stability and security aspects. To this, the behaviour of an SPC needs to be continuously supervised and controlled by a monitoring and control system whose main responsibilities are (i) to ensure the security and stability of the SPC and (ii) to guarantee that the SPC behaves in a supportive way with regard to the security and stability of the transmission grid at all times. Following this idea, the main objectives of the monitoring and control system of an SPC can be classified in internal and external objectives.

Internal objectives are related to enforcing a secure, stable and efficient operation of the cell itself. The main internal objectives are

- to supervise the voltage profiles within the SPC and control its PCUs (e.g. distributed generators, storages, flexible loads) and switching devices (e.g. circuit breakers, OLTC transformers) to ensure that pre-established voltage limits within the SPC are not violated,
- to supervise the loading situation of SPC components and control its PCUs and switching devices to ensure that pre-established loading limits (e.g. apparent power limits of lines and cables) are respected,
- to track the operating point of the SPC and its trajectory with regard to local stability limits and trigger corrective measures when the stability of the SPC is at risk,
- to supervise the overall SPC behaviour and control its PCUs and switching devices to optimize the operation of SPC according to technical and economic criteria.

In the other hand, external objectives are required for the secure, stable and efficient operation of the entire power system and mainly concentrate on the interactions and behaviour of an SPC from the transmission network perspective. Here it should be noted that the idea of organizing the distribution network level in SPCs is intended to be implemented in the context of an extensive decommission of conventional power plants. Thus, the external objectives of the monitoring and control system of an SPC are intended to guarantee that an SPC behaves in such a way that the properties of conventional power plants which are essential for the operation of the system today (see. section 2.4) can be substituted such that the system of the future can continue to be operated in a secure and efficient way, even if conventional power plants are entirely decommissioned.

Following this idea, the monitoring and control system of an SPC needs to reach the following external objectives:

- Coordinate the dynamic behaviour of SPC components such that - from a transmission network perspective - the entire SPC behaves dynamically in a supportive way e.g. by damping abrupt power balance changes at the transmission network level by coordinated virtual inertia or grid forming[5] converters within the SPC (substitution of inertia response and governor response capability of conventional power plants).
- Coordinate the flexibility and behaviour of SPC components to deliberately influence the active and reactive power exchange with the transmission network via its interface when this is requested by the transmission system operator e.g. for congestion management or voltage control at the transmission network level (substitution of re-dispatch response capability and voltage enforcement capability of conventional power plants).
- Estimate and provide forecasts of the available flexibility of the SPC to adjust the active and reactive power flow exchanged with the transmission network via its interface such that the TSO can coordinate the transmission system operation under knowledge of the available action space (required for the substitution of re-dispatch response capability due to increased uncertainty regarding the flexibility of SPCs in comparison to conventional power plants).
- Supervise and coordinate the behaviour of all SPC components for restoration activities after a blackout such as the black-start coordination of the cell in island mode and the synchronization with the transmission grid (substitution of the black-start capability of conventional power plants).

---

[5] Information about grid forming control schemes and methods can be found for instance in [4, 8, 18, 69, 92, 101]

3.5 Measurement equipment required for the operation of a Smart Power Cell

In order to supervise the states of SPC components and coordinate the behaviour of CPCUs and remote controllable switching devices such as circuit breakers and OLTC transformers, the monitoring and control system of an SPC needs information regarding the state of the grid and the instantaneous operation state of PCUs. To this, relevant physical quantities need to be mapped and made available by measurement equipment. In Fig. 3.1 selected measurement devices are illustrated with yellow symbols. However, it should be noted that the decision about what physical quantities need to be measured by specialized measuring equipment can only be made depending on the control schemes and supervision algorithms implemented within the SPC frame.

The most important quantities which need to be measured in order to supervise the state of the electric grid of an SPC are:

- the voltage amplitude of SPC buses
- the voltage angle of SPC buses
- the current amplitude of SPC lines and cables
- the current angle of SPC lines and cables
- the current amplitude of PCUs
- the current angle of PCUs

Other quantities of interest can be derived from these quantities, for example:

- the active power flow over lines and cables
- the reactive power flow over lines and cables
- the active power behaviour of PCUs
- the reactive power behaviour of PCUs

Depending on the control schemes and supervision algorithms implemented, more or less measuring points will be required. Further, in case a full image of the state of the grid is required, a state estimation algorithm can be needed. These design details, however, can only be specified when the decision on the implementation of particular algorithms for supervision and control has been taken. In this chapter, only a general description of the SPC concept is provided. A supervision and control scheme which can be applied in an SPC is described in detail in chapter 6.

3.6 Communication infrastructure required for the operation of a Smart Power Cell

In order to continuously supervise the security and stability of an SPC and to influence its behaviour when required, its monitoring and control system needs to be able to acquire data from measurement devices and to send control data to controllable resources such as controllable PCUs and switching devices. Furthermore, in order to guarantee that the behaviour of SPCs support the security and stability of the transmission network, their monitoring and control systems need to be able to exchange information with monitoring and control entities of the transmission network.

A communication architecture to support the suggested concept has been discussed in previous work [DM13] and will not be described here in detail. Note also that in Fig. 3.1 the communication network is not illustrated explicitly, but the presence of communication links is suggested by the red dots.

3.7 Description of the interface between a Smart Power Cell and the transmission network

In a power system organized according to the SPC concept, SPCs interact with the transmission network via clear defined interfaces. In this section, these interfaces are addressed and relevant terms and concepts are introduced. These terms and concepts are used throughout the thesis and are useful to describe and understand how an SPC interacts with the transmission network.

Fig. 3.10 shows a schematic representation of the interface between a transmission network bus and an SPC. The upper part of the figure shows a line diagram which describes the topology of the interface. The lower part of the figure shows the corresponding single-phase equivalent circuit.

The interface between the transmission network (grey area) and the SPC (green area) is given by the Interconnection Bus (IB) which is highlighted in red. This bus embodies the coupling point between the two systems and enables their interaction. The interconnection bus is connected to a bus of the transmission network (bus HV-1) via a high voltage line and to a bus of the SPC (bus MV-1) via an OLTC transformer. The complex interconnection voltage $\bar{V}^{\mathrm{IB}}$, which is the voltage at the interconnection bus, depends on both the operating point of the transmission network and the operating point of the SPC and can be seen as a coupling state between both systems. The current which flows from the

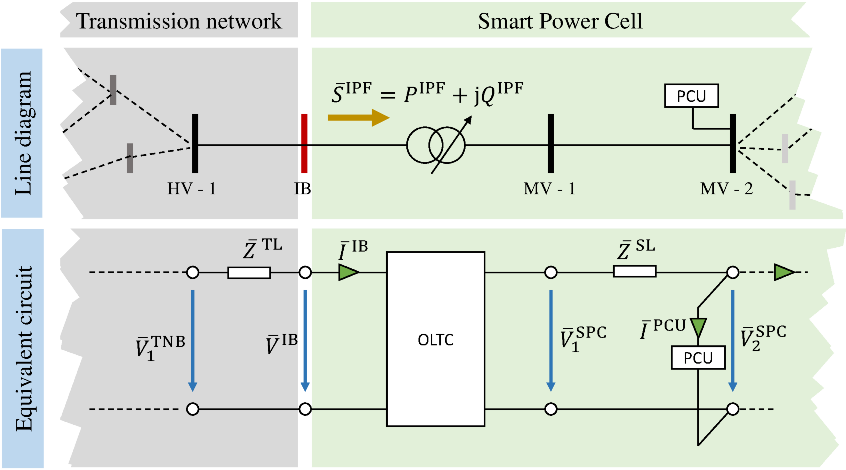


Figure 3.10: Schematic representation of the interface between a transmission network bus and an SPC

interconnection bus into the SPC is called interconnection current $\bar{I}^{\mathrm{IB}}$. This current results from the sum of all currents injected and consumed by all the PCUs within the SPC.

Departing from these two quantities (the interconnection voltage $\bar{V}^{\mathrm{IB}}$ and the interconnection current $\bar{I}^{\mathrm{IB}}$) the apparent power which an SPC withdraws from the transmission network can be determined by

$$\bar{S}^{\mathrm{IPF}} = P^{\mathrm{IPF}} + \mathrm{j}Q^{\mathrm{IPF}} = 3\bar{V}^{\mathrm{IB}}(\bar{I}^{\mathrm{IB}})^{*} \tag{3.4}$$

This power flow is helpful to describe the interaction of an SPC with the transmission network and therefore, a name and a definition for this physical quantity is introduced at this point:

Definition 2 (Interconnection Power Flow - IPF)**.** *The IPF of an SPC is defined as the apparent power* $\bar{S}_n^{\mathrm{IPF}} = P_n^{\mathrm{IPF}} + \mathrm{j}Q_n^{\mathrm{IPF}}$ *which is consumed by an SPC* n *from the transmission network via its interface. For* $P_n^{\mathrm{IPF}} > 0$ *and* $Q_n^{\mathrm{IPF}} > 0$*, the SPC behaves from TSO perspective as an inductive load. For* $P_n^{\mathrm{IPF}} < 0$ *and* $Q_n^{\mathrm{IPF}} < 0$*, the SPC behaves from transmission network perspective as a capacitive generator.*

Here, the following should be noted: For $P_n^{\mathrm{IPF}} < 0$, the SPC does not behave as a load. Instead it injects active power into the transmission network.

The interconnection voltage $\bar{V}^{\mathrm{IB}}$ continuously adjusts itself depending on the state of the transmission network and the SPC. The interconnection current $\bar{I}^{\text{IB}}$ depends on the other hand on the sum of currents injected and withdrawn by PCUs connected within the SPC. If a PCU changes its active and or reactive power behaviour, this leads to a change in the current injected or withdrawn by that particular unit and this, in turn, results in a change in the interconnection current $\bar{I}^{\text{IB}}$. Thus, according to equation 3.4 a change in the active or reactive power behaviour of any PCU of a particular SPC also leads to a change in its IPF. At this point, however, it is important to note that not only the active and reactive power behaviour of PCUs impacts the IPF but also the apparent power losses of the lines and cables of the SPC.

The following equations describe the dependency of the IPF of an SPC depending on the power injection and consumption of PCUs and on losses within the system. Note that in the equations a differentiation between controllable and non-controllable PCUs is made. The active IPF P_n^{IPF} of a particular SPC n can be expressed by

$$P_n^{\text{IPF}} = \sum_{d \in D_n} P_d^{\text{NPCU}} + \sum_{l \in L_n} P_l^{\text{loss}} + \sum_{r \in R_n} P_r^{\text{CPCU}}, \tag{3.5}$$

where P_d^{NPCU} is the active power behaviour of the non-controllable PCU $d \in D_n$, P_l^{loss} is the active power loss of line $l \in L_n$ and P_r^{CPCU} is the active power behaviour of the controllable PCU $r \in R_n$. Here, D_n, L_n and R_n are the sets of non-controllable PCUs, lines and controllable PCUs which belong to the SPC n.

The reactive IPF Q_n^{IPF} of SPC n can be expressed by

$$Q_n^{\text{IPF}} = \sum_{d \in D_n} Q_d^{\text{NPCU}} + \sum_{l \in L_n} Q_l^{\text{loss}} + \sum_{r \in R_n} Q_r^{\text{CPCU}}, \tag{3.6}$$

Here, Q_d^{NPCU} is the reactive power behaviour of the non-controllable PCU $d \in D_n$, Q_l^{loss} is the reactive power loss of line $l \in L_n$ and Q_r^{CPCU} is the reactive power behaviour of the controllable PCU $r \in R_n$.

From the transmission network perspective, the behaviour of an SPC can be described by the corresponding interconnection voltage $\bar{V}^{\text{IB}}$ and the IPF $\bar{S}^{\text{IPF}}$. The IPF of an SPC at a given moment can be visually represented as a point in the P-Q plane. The same can be done for the apparent power behaviour of PCUs and the losses over lines and cables. This leads to the visual representation of equations 3.5 and 3.6 which is depicted in figure 3.11.

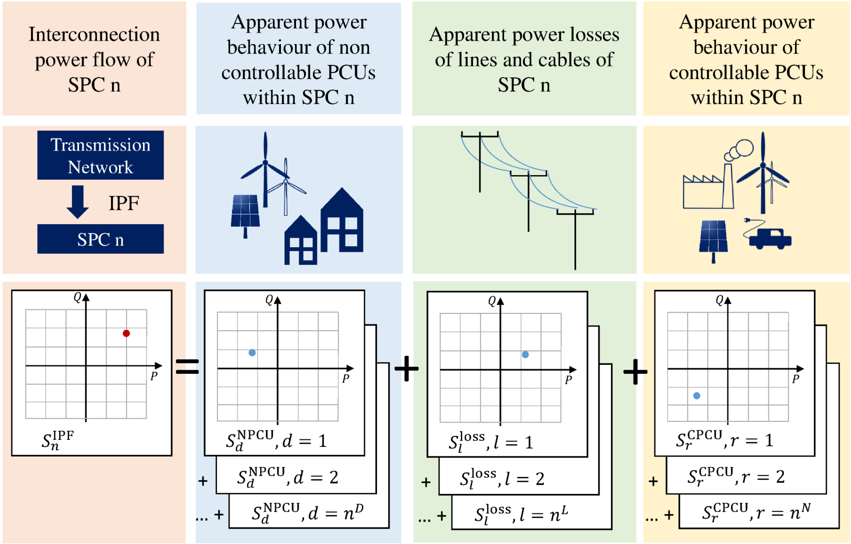


Figure 3.11: The dependency of the interconnection power flow of an SPC on the apparent behaviour of its components

3.8 Dynamic behaviour of a Smart Power Cell and its Input-Output description

An SPC can be treated as a dynamic system whose operating point varies over time depending on its previous position and the influence of physical quantities which have an impact on it. Such a system can be modelled with a set of hybrid algebraic differential equations which relate how a set of variables - the output and the state variables of the system - evolve over time depending on a set of input variables. The input and output variables of an SPC are depicted in Fig. 3.12. The green block in the centre of the figure represents an SPC including its components and its monitoring and control system. The input variables are depicted as arrows on the left side of the figure. The outputs are depicted on the right side. As the figure shows, the dynamic behaviour of an SPC depends on its interconnection voltage $\bar{V}^{\mathrm{IB}}$, which is the voltage at the interconnection bus which interlinks the transmission network with the SPC and the external determinants vector $\mathbf{e}^{\mathrm{SPC}}$. The interconnection voltage $\bar{V}^{\mathrm{IB}}$ depends on the behaviour of the transmission network and the SPC itself and can, therefore, be seen as the coupling state between both systems. The external determinant

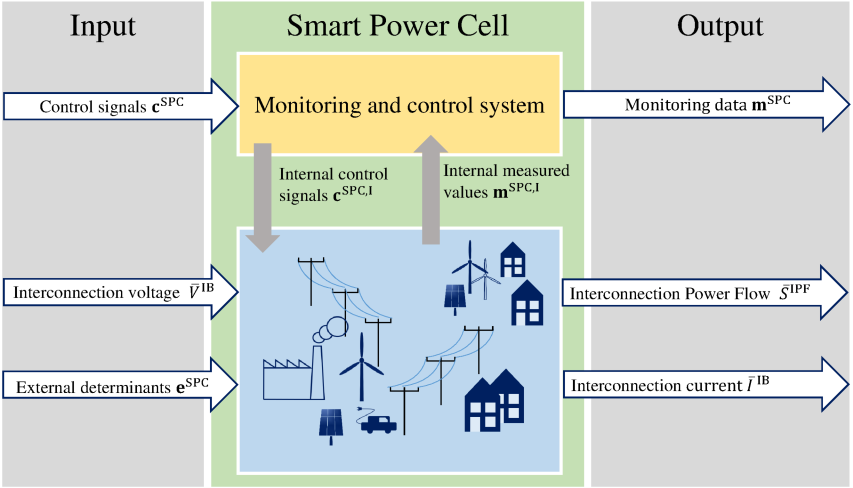


Figure 3.12: Schematic overview of the inputs and outputs of an SPC

vector $\mathbf{e}^{\mathrm{SPC}}$ is a vector which maps several signals of the environment of the SPC which have an influence on its behaviour. These signals map for example the wind speed which has an impact on the behaviour of wind energy converters within the SPC or the solar radiation which has an impact on the behaviour of PV-units. Other examples for signals which are mapped by this vector are for example those, who have an impact on the behaviour of households loads such as the time, the temperature and the day of the week.

Since an SPC is a monitored and controlled entity, which can adapt its behaviour in order to support the operation of the transmission network, its dynamic behaviour also depends on external control signals which are provided by a superimposed monitoring and control system at the transmission network level. These signals are mapped by the control signal vector $\mathbf{c}^{\mathrm{SPC}}$, which includes e.g. reference values for the IPF of an SPC or instructions concerning the dynamic behaviour of the cell (e.g. maximum rate of change of output signals in case of input changes).

The dynamic behaviour of an SPC can be understood as the set of rules which describes how the system behaves when input signals change over time departing from a known initial operating point. These changes lead to a dynamic transition in which all components within the SPC interact with each other until a new point of equilibrium is reached. The evolution rule of an SPC, which can be

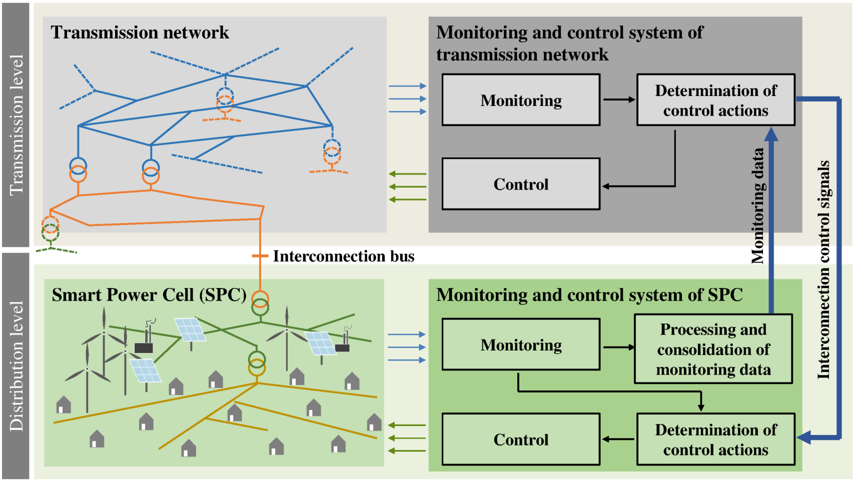


Figure 3.13: Cross voltage level monitoring and control concept

described as a set of hybrid, non-linear, algebraic differential equations (see chapter 4), results from the coupling of the dynamic models of the components of the SPC and the models of its controllers.

3.9 Cross voltage level coordination of Smart Power Cells for the secure and efficient operation of future power systems

The main objective of reorganizing the power system according to the SPC concept is to enable its secure, stable and efficient operation without the need of conventional power plants. This is possible due to the fact that - unlike passive distribution networks - SPCs are monitorable and controllable entities which can be controlled such that their behaviour can be adjusted and controlled on demand. Due to this property, in a power system organized according to the SPC concept, a TSO can supervise and coordinate the SPCs connected to its responsibility area in such a way that the interventions which today rely on conventional power plants can be performed by controlling their behaviour. A schematic overview of a monitoring and control concept to meet this objective is depicted in figure 3.13. The upper part of the figure corresponds to the transmission network domain. The lower part of the figure corresponds to the distribution network domain. Note that only one SPC is illustrated, but the same monitoring and control structure is valid for the remaining SPCs connected to the transmission network.

As the figure shows, the transmission system is monitored by a Monitoring and Control System (MACS) which determines control actions which are carried out whenever this is necessary to meet security and efficiency requirements. As the illustration depicts, the determination of control actions is based on the state of the transmission system which is continuously supervised by its MACS. In contrast to the way the system is currently operated, the control actions at the transmission network level do not focus on coordinating the behaviour of conventional power plants. Instead, the state of the transmission system is mainly influenced by changes in the topology of the network (e.g. switching of circuit breakers), changes in the electric characteristics of the network (e.g. controlling load flow control devices), controlling the behaviour of High-Voltage Direct Current (HVDC) links and, in particular, coordinating the behaviour of SPCs. To this, the MACS of the transmission system continuously acquires condensed monitoring data which is periodically provided by the MACSs of SPCs. The monitoring data of SPCs describe their current behaviour and also provide estimations of their flexibility to adapt their future behaviour if requested by the TSO. Based on the collected monitoring data, the MACS of the transmission network periodically determines control signals for all its SPCs in order to enforce that the transmission network is operated in an efficient way and that its state is secure and stable. The interconnection control signals provided by the TSO describe a desired behaviour which the MACSs of the SPCs need to meet as long as the changes required do not put their stability or security at risk. To this, the behaviour of controllable PCUs and switching devices within the SPCs are coordinated in order to meet the control instructions provided by the TSO while the state of the components installed within the SPC are continuously supervised in order to avoid the violation of any security limit or put the stability of the system at risk.

The monitoring data provided by the MACSs of SPCs for cross voltage level condination can for instance include:

- Data describing the operation of an SPC at a particular instant (snapshot) such as the instantaneous interconnection voltage $\bar{V}^{\mathrm{IB}}$, the instantaneous interconnection current $\bar{I}^{\mathrm{IB}}$ and the instantaneous IPF $\bar{S}^{\mathrm{IPF}} = P^{\mathrm{IPF}} + \mathrm{j}Q^{\mathrm{IPF}}$.
- Data describing the flexibility of an SPC to adapt its behaviour according to the requirements of the TSO such as the region in which the IPF can

be adjusted to support the operation of the transmission network (see also chapter 5).

- Data describing the dynamic behaviour which an SPC is expected to adopt in case the TSO requests a particular change in its behaviour such as the maximum and minimum rate of change of the active IPF - $P^{\mathrm{IPF,ROC,min}} < \frac{dP^{\mathrm{IPF}}}{dt} < P^{\mathrm{IPF,ROC,max}}$ - and the maximum and minimum rate of change of the reactive IPF - $Q^{\mathrm{IPF,ROC,min}} < \frac{dQ^{\mathrm{IPF}}}{dt} < Q^{\mathrm{IPF,ROC,max}}$.
- Data describing the time-variant dynamic behaviour of an SPC (e.g. in the form of a reduced dynamic model) such that the TSO can consider its behaviour in the context of system-wide stability and security studies.

The interconnection control signals provided by the MACS of the transmission network to request changes of the behaviour of an SPC can for instance include:

- Interconnection set points such as interconnection voltage set points $V^{\mathrm{IB,ref}}$, interconnection current set points $I^{\mathrm{IB,ref}}$ and IPF set points $\bar{S}^{\mathrm{IPF,ref}} = P^{\mathrm{IPF,ref}} + \mathrm{j}Q^{\mathrm{IPF,ref}}$.
- Requirements and set points regarding the dynamic behaviour which the SPC needs to adopt when interconnection set points are changed. This can for example include a desired active IPF rate of change - $\frac{dP^{\mathrm{IPF}}}{dt} = P^{\mathrm{IPF,ROC,ref}}$ - and a desired reactive IPF rate of change - $\frac{dQ^{\mathrm{IPF}}}{dt} = Q^{\mathrm{IPF,ROC,ref}}$.
- Requirements and set points regarding the dynamic behaviour which the SPC needs to adopt when influencing factors change abruptly or perturbations of the system state occur. This can for example include a desired behaviour of the grid forming controller during abrupt active power changes.
- Requirements and control instructions for the coordination of the restoration and synchronization processes for system restart after a blackout.

3.10 The role of Smart Power Cells in the operation of future power systems

The SPC concept aims at enabling a future power system to be operated without conventional power plants. To this, SPCs need to be integrated in the operation of the system in such a way that all interventions which are essential for its secure, stable and efficient operation (see section 2.3) and today rely on the properties and capabilities of conventional power plants (see section 2.4) can be substituted.

Regarding the instantaneous time scale, this means that SPCs need to be able to assume the interventions required to form the frequency and voltage and to react almost instantaneously to sudden state changes, such that the stability of the system can be continuously guaranteed (See also section 2.2.2). In this context SPCs need to be able to

- form[6] and control the frequency of the system (e.g by coordinating the grid forming behaviour and the active power provision of its PCUs),
- form and control the voltage of SPC buses and by this impose the voltage of its interconnection bus (e.g. by coordinating the grid forming behaviour and the reactive power provision of its PCUs),
- trigger protection actions in case of faults and sudden sate changes.

Regarding the real-time scale, SPCs need to be able to follow set points and instructions provided by a superimposed monitoring and control system, such that the state of the entire network can be influenced by coordinated changes in their behaviour. By this, SPCs can participate in the real-time operation of the system and become the foundation of its real-time operability. Thus, SPCs can substitute the role of conventional power plants and be involved on the interventions which are required for

- corrective congestion management,
- system-wide balancing of generation and load,
- real time system optimization (e.g. reduction of losses or generation costs) and
- system restoration after a black out.

Regarding the scheduling time scale, SPCs need to be integrated into the day-ahead and intraday operational planning of the system. This results from the fact that in a power system organized according to the SPC concept the operational planning will not focus on determining in advance which conventional power plants will participate in providing the power required to supply the system load. Instead, the core task will be the ex-ante planning of the behaviour of SPCs aiming at finding a preliminary operation point in which active and reactive power injections and withdrawals at the transmission network level are balanced and no security limits are violated. To this, SPCs need to provide forecasts and estimations of their future flexibility to react to set points and instructions

---

[6] Information about grid forming control schemes and methods can be found for instance in [4, 8, 18, 69, 92, 101]

provided by the TSO such that the system operation can be planned under consideration of the aggregated flexibilities of the PCU connected at SPC level. These forecasts and estimations can be used by the TSO to plan in advance the active and reactive power behaviour of SPCs such that a preliminary (day-ahead and intraday) operation plan can be defined. This preliminary schedule - which is the result of a multilateral agreement which can be expected to be market-driven under consideration of the technical limits of the system - can be thought of as a roadmap which needs to be followed by SPCs to the extent possible such that only unforeseen deviations (e.g. due to forecast errors) need to be counteracted by real-time and instantaneous interventions. In order to ensure that real-time and instantaneous interventions can be conducted when required, also the reserves which SPCs need to hold free, need to be planned and scheduled in advance. The allocation of reserves can also be expected to be organized by a market-driven process.

Regarding the long-term time scale, TSOs need to ensure that generation, transmission and distribution capacity is sufficient to guarantee the security of supply in the long term. In this context, the main task of TSOs will consist on supervising that the long-term operational flexibility of all SPCs connected to a transmission network is sufficient to maintain a system-wide active and reactive power balance without causing any limit or stability violation. Here, it is important to consider that in a power system organized following the SPC concept, there are no "conventional power plants" connected to the transmission network which need to supply the "loads" of the system. Instead, in a power system organized according to the SPC concept, the main task of TSOs regarding the long-term system planning is to ensure that the installed generation and storage capacities within SPCs and their resulting flexibility to adapt their behaviour are in the long term sufficient to ensure that the active and reactive power in the system can be kept balanced even in case of extreme weather scenarios. In this context, it is important to emphasize that SPCs do not pursue energy autonomy since this work is built upon the assumption that in future the growing unequal distribution of renewable energy production in place and time will lead to an increased need of cross-regional energy balancing.

To bring the SPC concept to life, intensive research efforts and developments in many different areas are still required:

- New monitoring, protection and control strategies and schemes for distribution and transmission grids need to be developed, tested, and implemented in order to enable the participation of SPCs in the instantaneous operation of the system.

- Operational concepts and control schemes need to be designed to integrate SPCs in the real-time operation of the system.
- New market frameworks and scheduling procedures under consideration of the new system architecture and increased responsibilities of system users need to be conceived and established such that SPCs can be involved in the operational planning of the system.
- The way the power system is planned in the long term must be fully reviewed and modified such that the reliable operation of the system can continue to be guaranteed despite the increasing planning complexity and uncertainty.
- The ICT-infrastructure needs to be extended such that monitoring and control entities of the transmission and distribution domain can collect data from measurement devices, send control data to controllable resources and communicate with each other reliably and at sufficient speed.
- The way power systems are modelled, simulated and analysed needs to be revised and new methods for the execution of security and stability studies under consideration of the increasing ICT dependency of the system need to be developed.
- The current regulation, technical guidelines and network codes need to be revised and adjusted as soon as possible such that involved parties such as manufacturer, utilities, transmission and distribution operators, regulatory entities and academic institutions can start adapting their processes, products and research and development emphasis such that the transformation of the system can be achieved in time.

Treating all these research areas within this dissertation in a comprehensive and detailed way would result in an impossible undertaking. Therefore, in the next chapters, the focus is set on selected problems and solutions which we expect will contribute to the development of the technology and methods which will enable to bring the SPC concept to life.

3.11 Summary

In the previous sections, a system architecture and operational concept for future low emission power systems have been presented. The developed architecture is founded on the idea of organizing the distribution level of future power systems in supervised and controlled grid subsections called Smart Power Cells which are perceived from the transmission network perspective as single monitorable and controllable entities that can adapt their dynamic behaviour on demand and by this be integrated in the operation of the transmission system. The main motivation for organizing a power system according to the SPC concept is to enable its secure and efficient operation without the need of conventional power plants.

In the next chapter, classic power system modelling techniques are reviewed and the adaptations required to use these techniques in the context of power systems organized following the SPC concept are discussed. In particular, a modelling framework is introduced which aims at providing a foundation for the development of operational concepts and control schemes for future power systems organized following the SPC concept.

Subsequently, chapter 5 describes a methodology to estimate the flexibility of a Smart Power Cell to adapt its behaviour (changes of its active and reactive IPF) when this is requested by the monitoring and control system of the transmission network. At the end of the chapter, the method is demonstrated in a test system which was developed for this purpose and can be used to test other methods of similar type.

Then, chapter 6 presents a control scheme which can be implemented in a Smart Power Cell such that its Interconnection Power Flow can be controlled in real-time to follow set points provided by the monitoring and control system of the transmission network. The control scheme is implemented in a test system and tested in a dynamic simulation which enables to study how an SPC dynamically behaves when its IPF is being controlled. In particular, the simulation shows that the designed control scheme is able to coordinate the behaviour of PCUs within the SPC to meet the control instructions provided by the monitoring and control system of the transmission network while internal security limits are continuously respected.

Finally, as a proof of concept, in chapter 7 the dynamic behaviour of a future power system organized according to the SPC concept is studied by a combined transmission-distribution test system which was specially designed for this purpose. The conducted dynamic simulations show how the behaviour of the SPCs connected to a transmission network can be controlled according to set points provided by a superimposed monitoring and control system to influence the state of the transmission network such that overloads and voltage problems can be solved.

4 Modelling and simulation of contemporary and future power systems

An electric power system can be thought of as a System-Of-Systems composed of a large number of diverse devices which are interconnected by an electric grid. The interplay of these devices with the grid and among themselves in a given context - i.e. under a particular scenario of internal or external stimuli - determines the way the system behaves. For system operators, system planners, component manufacturers, researchers, regulatory authorities and other stakeholders it is crucial to be able to understand how a power system behaves and how its behaviour can be influenced. Thus, from the mid-19th century onwards, there have been significant research efforts to find mathematical representations aiming to enable the modelling and simulation of electrical networks and their components. As a result, today, a wide range of well established methods and models have been documented in literature [41, 54, 66, 71, 79] and several power system modelling and simulation software tools are available.

In general, the state of the art methods to analyse power systems can be categorized into two groups: static and dynamic analysis techniques [66]. Static analysis techniques study the behaviour of power systems considering operational snapshots under a set of assumption. These methods are widely used in practice due to the relatively simple models that are required. On the other hand, dynamic analysis techniques study the behaviour of the system over time which makes possible to study the trajectories of system variables during a dynamic transition.

Due to the extensive decommissioning of conventional power plants and the integration of new components, the architecture and operation of power systems need to be re-engineered. As a result, many changes can be expected which will indeed have a significant impact on the way the system behaves. Thus, to guarantee the resilience of future power systems, comprehensive studies will need to be conducted, in order to understand how the behaviour of future power systems will change. In this context, finding suitable mathematical representations and developing methods to investigate the behaviour of future power systems is essential.

The next two sections give a general formulation of the state of the art models and methods used for static and dynamic power system analysis based on [41] and [65]. Subsequently, simplifications which are common practice today, but seem to be unfeasible for the analysis of future systems, are discussed. Finally, the chapter closes with a general description of a model which can be used to study the behaviour of future power systems under consideration of the SPC concept. In this section, only an abstract description of the models of the subsystems of a future power system is given. Implementations of these models are described in the chapters 5, 6 and 7.

4.1 Load flow analysis

The static behaviour of an electric grid can be determined by a power flow analysis which is based on the nodal Root Mean Square (RMS) description of an electric grid given by

$$\mathbf{i}^{\mathrm{N}} = \mathbf{Y}^{\mathrm{N}} \cdot \mathbf{v}^{\mathrm{N}}. \tag{4.1}$$

Here, the admittance matrix $\mathbf{Y}^{\mathrm{N}}$ relates the nodal current injection vector

$$\mathbf{i}^{\mathrm{N}} = [\bar{I}_1^{\mathrm{N}}, \bar{I}_2^{\mathrm{N}}, ..., \bar{I}_i^{\mathrm{N}}, ...\bar{I}_n^{\mathrm{N}}]^T \tag{4.2}$$

to the nodal voltage vector

$$\mathbf{v}^{\mathrm{N}} = [\bar{V}_1^{\mathrm{N}}, \bar{V}_2^{\mathrm{N}}, ..., \bar{V}_i^{\mathrm{N}}, ..., \bar{V}_n^{\mathrm{N}}]^T. \tag{4.3}$$

The i-th element $\bar{I}_i^{\mathrm{N}}$ of the vector $\mathbf{i}^{\mathrm{N}}$ stands for the complex nodal current injected at bus i of the modelled system while the i-th element $\bar{V}_i^{\mathrm{N}}$ of the vector $\mathbf{v}^{\mathrm{N}}$ represents the complex line-to-neutral voltage of bus i. [41, 65]

Furthermore, taking into account that the nodal complex power injections

$$\mathbf{s}^{\mathrm{N}} = [\bar{S}_1^{\mathrm{N}}, \bar{S}_2^{\mathrm{N}}, ..., \bar{S}_i^{\mathrm{N}}, ...\bar{S}_n^{\mathrm{N}}]^T \tag{4.4}$$

can be expressed with

$$\mathbf{s}^{\mathrm{N}} = \mathbf{V}^{\mathrm{N,diag}} \cdot \mathbf{i}^{\mathrm{N}*}, \tag{4.5}$$

where

$$\mathbf{V}^{\mathrm{N,diag}} = diag(\bar{V}_1^{\mathrm{N}}, \bar{V}_2^{\mathrm{N}}, ..., \bar{V}_i^{\mathrm{N}}, ..., \bar{V}_n^{\mathrm{N}}), \tag{4.6}$$

the well known load flow equations in vectorial form can be derived by substituting equation 4.1 in equation 4.5:

$$\mathbf{s}^{\mathrm{N}} = \mathbf{V}^{\mathrm{N,diag}} \cdot \mathbf{Y}^{\mathrm{N}*} \cdot \mathbf{v}^{\mathrm{N}*}. \tag{4.7}$$

This fundamental relation (equation 4.7) can be used to determine the state (snapshot) of an electric grid when enough information to solve the equation is provided. In the classical load flow analysis, this is enforced by classifying system buses into three bus types - Slack, PV and PQ buses - where certain variables are assumed to be known under the assumption that system controllers are able to keep particular system variables fixed according to predefined reference values. [41, 65]

Under these assumptions, the problem

$$\mathbf{0} = \mathbf{s}^{\mathrm{N}} - \mathbf{V}^{\mathrm{N,diag}} \cdot \mathbf{Y}^{\mathrm{N}*} \cdot \mathbf{v}^{\mathrm{N}*}, \tag{4.8}$$

can be solved using a numerical root-finding algorithm as the Newton-Raphson method. The objective is to find a vector $\mathbf{v}^{\mathrm{N}}$ which leads to a solution of equation 4.8 when a particular input scenario is given. The identified value of $\mathbf{v}^{\mathrm{N}}$ fully describes the state of the electric grid at a particular operating point and can be used for the determination of other values of interest, such as load flows or power losses over the system lines, since both, the load flows and the losses are functions of $\mathbf{v}^{\mathrm{N}}$. [41, 65]

If the lines are modelled as π-equivalents as suggested in [41], the power flow over a line connecting a specific node i with a specific node j of the grid can be written as

$$\bar{S}_{ij}^{*} = P_{ij} - \mathrm{j}Q_{ij} = \bar{V}_i^{*}(\bar{V}_i - \bar{V}_j)\bar{Y}_{ij} + \bar{V}_i^{2}\bar{Y}_{i0}, \tag{4.9}$$

while the power flow in the opposite direction is described by

$$\bar{S}_{ji}^{*} = P_{ji} - \mathrm{j}Q_{ji} = \bar{V}_j^{*}(\bar{V}_j - \bar{V}_i)\bar{Y}_{ji} + \bar{V}_j^{2}\bar{Y}_{j0}. \tag{4.10}$$

The losses over the line connecting the nodes i and j can be obtained with

$$\bar{S}_{ij}^{\mathrm{loss}} = P_{ij}^{\mathrm{loss}} + jQ_{ij}^{\mathrm{loss}} = \bar{S}_{ij} + \bar{S}_{ji}. \tag{4.11}$$

In summary: the steady-state of an electrical grid can be described with the complex voltage vector $\mathbf{v}^{\mathrm{N}}$ which can be found by a root-finding algorithm applied to solve the problem described by equation 4.8 by defining enough input parameters by classifying grid buses into Slack, PV and PQ buses. A detailed description of this method can be found in [41] and [65]. MATPOWER, an open source MATLAB implementation of the load flow problem, is available for download and can be freely used for research purposes. More information regarding MATPOWER can be found e.g. in [102].

A load flow analysis can be conducted to asses the state of an electric grid assuming steady-state operation conditions. As a result, the main quantities which describe the operating state of the electric grid under a given scenario can be determined and thus risks regarding voltage limit violations or overloading of system components can be identified. Also, for assessing if the operation of the system at a given moment is n-1 compliant, consecutive load flow calculations for a set of pre-established contingencies can be conducted. However, when risks due to instability need to be assessed, the steady-state description of the system is not sufficient and its dynamic behaviour, in particular during dynamic transitions after relevant events, needs to be studied. A method for analysing the dynamic behaviour of a power system is discussed in the next section.

4.2 Classic transient stability studies

As stated above, an electric power system is composed of several components which are interconnected by an electric grid. The interplay of these devices with the grid and among themselves determine the dynamic behaviour of the system. When the dynamic behaviour of a power system is to be investigated, both the electric grid and the power injecting and consuming components need to be modelled in detail. [65]

A common model for transient stability studies is the current-injection model described in [65]. Following this modelling approach, each power plant or load belonging to a power system can be modelled as a dynamic system described by a set of algebraic-differential equations whose input is the voltage of its connection bus and whose output is the current injected into its connection bus. Power plant models can include additional inputs to map reference values such as frequency and voltage set points. A detailed description of the models used to mathematically describe the dynamic behaviour of power plants and conventional loads can be found in [65, 79].

Assuming three-phase positive sequence conditions and neglecting electromagnetic transients, the electric grid, which interconnects the power plants and loads, can be modelled - as discussed in the previous section 4.1 - by an admittance matrix and the algebraic relationship given by equation 4.1 [79]. By coupling the models of power plants and loads with the electric grid model the following set of non-linear algebraic-differential equations can be obtained [65]:

$$\dot{\mathbf{x}} = \boldsymbol{f}(\mathbf{x}, \mathbf{v}^{\mathrm{N}}, \hat{\mathbf{y}}, \boldsymbol{\eta}) \tag{4.12a}$$

$$\mathbf{0} = \hat{\boldsymbol{g}}(\mathbf{x}, \mathbf{v}^{\mathrm{N}}, \hat{\mathbf{y}}, \boldsymbol{\eta}) \tag{4.12b}$$

$$\mathbf{0} = \mathbf{i}^{\mathrm{N}}(\mathbf{x}, \mathbf{v}^{\mathrm{N}}, \hat{\mathbf{y}}, \eta) - \mathbf{Y}^{\mathrm{N}}(\mathbf{x}, \boldsymbol{\eta})\mathbf{v}^{\mathrm{N}} \tag{4.12c}$$

Here,

- $\mathbf{x}$ ($\mathbf{x} \in \mathbb{R}^{n_x}$) is the state vector,
- $\mathbf{v}^{\mathrm{N}}$ is the nodal voltage vector,
- $\hat{\mathbf{y}}$ is a vector of additional algebraic variables and
- $\boldsymbol{\eta}$ a vector of controllable parameters.

The sets of equations 4.12a and 4.12b are composed of the sets of algebraic-differential equations which describe the dynamic behaviour of power plants and loads. The set of algebraic equations 4.12c describes the behaviour of the grid by relating the outputs of the power plants and load models (mapped by the nodal current vector $\mathbf{i}^{\mathrm{N}}$) with their inputs (mapped by the nodal voltage vector $\mathbf{v}^{\mathrm{N}}$). Here, the relation between $\mathbf{i}^{\mathrm{N}}$ and $\mathbf{v}^{\mathrm{N}}$ is given by the nodal admittance matrix $\mathbf{Y}^{\mathrm{N}}$. Note that the nodal admittance matrix $\mathbf{Y}^{\mathrm{N}}$ is a function of the state vector $\mathbf{x}$ and the vector $\boldsymbol{\eta}$ such that changes in the electric description of the grid due to control actions, tapping of regulating transformers or disturbances can be mapped. [66]

The model given by the equations 4.12a, 4.12b and 4.12c can be treated as an initial-value problem which can be solved using a numerical integration method when the initial values $\mathbf{x}(t_0)$, $\mathbf{v}^{\mathrm{N}}(t_0)$, $\hat{\mathbf{y}}(t_0)$ and $\boldsymbol{\eta}(t_0)$ are known. To this, an initial operating point of the electric grid needs to be found by a load flow analysis. The results of the load flow analysis are subsequently used to calculate the initial values of the vectors $\mathbf{x}$ and $\hat{\mathbf{y}}$ [79]. In [66] this process is described in detail. Once all initial values of the system given by the equation 4.12a, 4.12b and 4.12c have been determined, the trajectories of $\mathbf{x}, \mathbf{v}^{\mathrm{N}}$ and $\hat{\mathbf{y}}$ can be approximated with a numerical integration method such as the Euler's method. [66]

The model described by the equations 4.12a, 4.12b and 4.12c is suitable for the simulation of large systems, in which fast dynamics are not considered and single-phase fundamental frequency behaviour is assumed. If fast dynamics are on the focus of study, Electromagnetic Transient (EMT) modelling and simulation techniques are required [49]. In this thesis, however, the study of fast electromagnetic transients is not treated, and thus, the associated EMT modelling and simulation of power systems is not addressed in detail.

4.3 Revision of common simplifications in the power system modelling context

Today, when wide-area load flow analysis and transient stability studies of conventional power systems are conducted, several simplifications are usually made. These simplifications were introduced to reduce the complexity of the modelling task and to limit the computation expensiveness of the load flow and transient stability problem. For conventional power systems, due to the way they are organized and operated, these simplifications are considered to be feasible. However, it is still not clear if these simplifications will continue to be suitable in the future, in particular, when new operational concepts - as the SPC concept - are taken into account.

It is e.g. common practice to model system components connected within the transmission network such as power plants, power lines, circuit breakers and Flexible Alternating Current Transmission Systems (FACTS) in detail and consider distribution networks as passive loads which are usually represented by highly simplified aggregated steady-state or dynamic load models [67]. In the past, this simplification was widely accepted, since distribution networks were considered to be passive subsystems which (i) arbitrarily consumed active and reactive power from the transmission network depending on external factors and (ii) were not able to adapt their behaviour to participate in the operation of the system. Thus, in the context of steady-state power system analysis, the behaviour of distribution networks is usually assumed to be given - e.g. based on load forecasts - and is usually represented with either (i) constant active and reactive power load models, (ii) combined constant impedance, constant current and constant power models or (iii) exponential load models. Accordingly, in the context of transient stability studies, distribution networks tend to be represented by very simplified steady-state or dynamic load models. An overview of the models commonly used in practise and academia for these purposes can be found e.g. in [67].

In the context of steady-state power system analysis, these simplifications have been considered to be suitable because it was assumed that considering the behaviour of distribution networks as power sinks was sufficient for operational planning and steady-state security assessment purposes. In the context of dynamic power system studies, these simplifications have been considered to be acceptable due to the assumption that the main transient phenomena which are relevant to study and asses the stability of a power system arise from the interactions of conventional power plants with the transmission network and that distribution networks only play a subordinate role on the dynamic behaviour of the system.

In a power system organized according to the SPC concept, however, these assumptions and simplifications can not be considered to be valid any more. In regard to operational planning and steady-state security assessment tasks, SPCs need to be considered as active subsystems which are able to adapt their behaviour on demand. Besides, in the context of dynamic power system studies, the transient behaviour of a power system organized according to the SPC concept will not be mainly determined by the dynamic behaviour of synchronous machines and governors of conventional power plants. Instead, the behaviour of PCUs such as Distributed Generators (DGs), loads and storages along with their controllers interacting in a coordinated way within SPCs will determine how the system dynamically behaves, especially when these devices are coordinated by means of cross voltage level control methods, e.g. for the provision of ancillary services across voltage levels. Therefore, in future, the accurate representation of the behaviour of SPCs including models of distributed generators, loads and storage systems along with their controllers will be a central task when the transient stability of a power system is to be assessed.

A further simplification which needs to be revised when power systems organized according to the SPC concept are modelled is the way in which the effects of communications processes are taken into account. When the security and stability of conventional power systems have been studied in the past, usually, information and communication technologies involved in the operation of the system have been either assumed as ideal and fully accessible or completely neglected. In a power system organized according to the SPC concept, however, a huge number of controlled devices across all voltage levels need to be coordinated in real-time, resulting in a system whose dynamic behaviour is directly influenced by the Information and Communications Technology (ICT)-infrastructure and its performance. Therefore, in future, the appropriate representation of the effects of communication processes, delays and faults will be decisive for the assessment of the security and stability of the system.

Another aspect which in the past has usually been neglected or considered in very simplified ways is the impact which external influencing factors such as the weather have on the behaviour of the power system. In a conventional system, changes in temperature, wind speed or solar radiation had only a slight impact on its dynamic behaviour. Thus, steady-state and dynamic power system models did usually not directly consider the impact of the weather. In a power system organized according to the SPC concept, however, the influence of the environment will be decisive. Thus, it can be expected, that mapping weather changes by an environment model and tracking how these changes impact the operability, security and stability of the system will be a critical issue when the behaviour of future systems is modelled and simulated.

In the context of modelling and simulation of conventional power systems, a lot of attention has been paid on the detailed modelling of the control structures of conventional power plants and their components. In fact, it was assumed that the controllers of conventional power plants and their components (prime mover control, automatic voltage regulator, power system stabilizer) not only impacted but determined the dynamic behaviour of the system. On the other hand, superimposed monitoring and control systems were not directly represented when the system was modelled. Instead, the impact of superimposed monitoring and control systems have been usually represented as input signals or events. As a result, the interdependencies and interactions between system components and superimposed monitoring and control systems were usually neglected. This was based on the idea that due to different time scales a simultaneous simulation of the network and the superimposed monitoring and control system was not necessary. In a power system organized according to the SPC concept, these simplifications will not be suitable any more, in particular, due to the increased dependency of the system on its superimposed monitoring and control structures. Besides, due to the developments of ICT-systems, the reaction speed of monitoring and control systems will increase, and this will require that the monitoring and control systems are taken into account when the dynamic behaviour of the system is studied.

4.4 Modelling and Simulation of future power systems organized according to the Smart Power Cell concept

According to the considerations discussed above, it is evident that for studying the steady-state and dynamic behaviour of a power system organized according to the SPC concept, many of the simplifications and assumptions which are widely accepted when conventional power systems are modelled can not be applied.

To study and analyse a future power system organized according to the SPC concept a more general and flexible model is required. This model needs to be able to reproduce the interactions of the transmission network with the SPCs connected to it. To this, not only the transmission network level needs to be modelled in detail. Instead, the mathematical description of the SPCs along with their components needs to be in the centre of attention. Further, due to the weather dependency of SPCs, the impact of the weather needs to be taken into account by means of an environment model which maps the evolution of e.g. the solar radiation, wind speed and temperature over time. Besides, due to the increased impact of superimposed monitoring and control systems on the behaviour of the transmission network but also SPCs, monitoring and control systems models will need to be directly considered when the system is modelled. In addition, since a power system organized according to the SPC concept will rely on the fast data exchange between measurement devices, PCUs and monitoring and control systems, the model needs to capture communication processes by a communication model.

An overview of a model which can be used to study the dynamic behaviour of a future power system organized according to the SPC concept is given by figure Fig. 4.1. The transmission system model (grey box) is composed of a model of the electric transmission grid and the models of the PCUs which are directly connected to it together with the associated control system models. SPC models are composed of an electric distribution grid model and the PCUs connected to it together with the associated control structures. Each modelled SPC is coupled with the transmission network model by the Interconnection Voltage $\bar{V}_n^{\mathrm{IV}}$ and the Interconnection Current $\bar{I}^{\mathrm{IC}}$. The Interconnection Power Flow (IPF) $\bar{S}_n^{\mathrm{IPF}}$ which the SPC n exchanges with the transmission system can be computed from these two quantities. The impact of the environment on the transmission system and the SPCs is mapped by the vectors $\mathbf{e}^{\mathrm{TS}}$ and $\mathbf{e}_n^{\mathrm{SPC}}$. These vectors are generated by an environment model. The transmission system and theSPC models are supervised and controlled by the superimposed monitoring and control model which get the monitoring signals $\mathbf{m}^{\mathrm{TS}}$ and $\mathbf{m}_n^{\mathrm{SPC}}$ and issues control instructions mapped by the vectors $\mathbf{c}^{\mathrm{TS}}$ and $\mathbf{c}_n^{\mathrm{SPC}}$. In addition, the superimposed monitoring and control system continuously gets updates of the vector $\mathbf{m}^{\mathrm{E}}$ which contains signals which map values of the environment which are assumed to be measured and supervised. In order to capture the impact

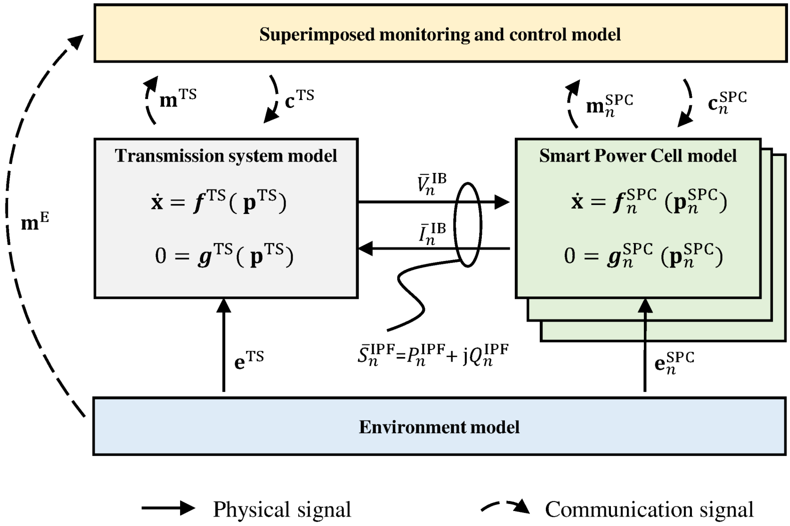


Figure 4.1: Schematic overview of the model structure of a future power system organized according to the Smart Power Cell concept

of data transmission and processing on the behaviour of the system, all signals which are assumed to be exchanged by means of an ICT system are delayed or in case of ICT-faults distorted by a communication model.

The dynamic power system model illustrated by Fig. 4.1 can be mathematically described by coupling the sets of equations which describe its subsystems. By this, a comprehensive dynamic model in the form of a set of non-linear and hybrid algebraic differential equations can be obtained:

$$\dot{\mathbf{x}} = \boldsymbol{f}(\mathbf{x}, \mathbf{y}, \mathbf{h}, \mathbf{u}, \mathbf{e}, \mathbf{m}, \mathbf{c}), \tag{4.13a}$$

$$0 = \boldsymbol{g}(\mathbf{x}, \mathbf{y}, \mathbf{h}, \mathbf{u}, \mathbf{e}, \mathbf{m}, \mathbf{c}). \tag{4.13b}$$

The model given by equation 4.13 defines how the quantities which describe the operating condition of the power system relate to each other. Depending on the properties, physical significance and corresponding domain of the considered quantities a categorization can be made leading to the definition of the vectors $\mathbf{x}, \mathbf{y}, \mathbf{h}, \mathbf{u}, \mathbf{e}, \mathbf{m}$ and $\mathbf{c}$ which embody the parameter space of the model. Here, $\mathbf{x}$ is a vector of dynamic states, $\mathbf{y}$ a vector of algebraic states and $\mathbf{h}$ a vector of discrete states. The vector $\mathbf{u}$ maps the active and reactive power behaviour of PCUs. The vector $\mathbf{e}$ maps external influencing factors which have an impact on the behaviour of the system. The vector $\mathbf{m}$ maps monitoring signals which are obtained from the physical system by measurement equipment or provided by monitoring and control systems of subsystems. The vector $\mathbf{c}$ maps control signals issued by monitoring and control systems. The vectors $\mathbf{x}, \mathbf{y}, \mathbf{h}, \mathbf{u}, \mathbf{e}, \mathbf{m}$ and $\mathbf{c}$ span the multidimensional parameter space $\mathcal{P}$. A point in $\mathcal{P}$ can be described by the vector $\mathbf{p}$:

$$\mathbf{p} = [\mathbf{x}^{\mathrm{T}}, \mathbf{y}^{\mathrm{T}}, \mathbf{h}^{\mathrm{T}}, \mathbf{u}^{\mathrm{T}}, \mathbf{e}^{\mathrm{T}}, \mathbf{m}^{\mathrm{T}}, \mathbf{c}^{\mathrm{T}}]^{\mathrm{T}}. \tag{4.14}$$

Note that in Fig. 4.1 this notation has been used. Thus, $\mathbf{p}^{\mathrm{TS}}$ stands for the operating point of the transmission network and $\mathbf{p}_n^{\mathrm{SPC}}$ stands for the operating point of a particular Smart Power Cell n. Note also that $\mathbf{p}^{\mathrm{TS}}$ and $\mathbf{p}_n^{\mathrm{SPC}}$ are subvectors of the vector $\mathbf{p}$ which describes the operating point of the entire system.

The model given by the set of equations 4.13 results from the coupling of the models that describe the behaviour of the subsystems of a future power system organized according to the SPC concept.

The model given by 4.13 is a dynamic model which can be used for the execution of transient studies, however, it should be noted that for

$$\dot{\mathbf{x}} = \boldsymbol{f}(\mathbf{x}, \mathbf{y}, \mathbf{h}, \mathbf{u}, \mathbf{e}, \mathbf{m}, \mathbf{c}) = 0, \tag{4.15}$$

a steady-state model can be obtained. The resulting model can be used for steady-state system studies.

In the next section, definitions of the vectors $\mathbf{x}, \mathbf{y}, \mathbf{h}, \mathbf{u}, \mathbf{e}, \mathbf{m}, \mathbf{c}$ and the corresponding parameter spaces are provided. Subsequently, the models of the subsystems depicted in Fig. 4.1, which compose the model of a future cyber-physical power system organized according to the SPC concept, are described in the sections 4.4.2 to 4.4.5. Additionally, a communication model which can be used to consider the impact of ICT on the behaviour of the system is described in section 4.4.6.

Note that in this chapter, only a general description of the models is given. A concrete implementation of a future power system model organized according to the SPC concept including simulation results is described in chapter 7.

4.4.1 Parameter space of the model of a future power system organized according to the Smart Power Cell concept

In this section, the parameter space of the model of a future power system organized according to the SPC concept depicted in is described. An overview of the model is given by the figure 4.1.

Dynamic state vector $\mathbf{x}$: The dynamic state vector $\mathbf{x}$ describes a point in the state space $\mathcal{X}$, which is the space of all possibles dynamic states that the modelled system can adopt. The system variables described by dynamic states are variables whose values evolve over time depending on their own values and other input variables following the relations described by equation 4.13a. System variables which can be modelled as state variables are for example the rotational speed of a synchronous generator or the state variable of an integrator belonging to a PI-controller.

Algebraic state vector $\mathbf{y}$: The algebraic state vector $\mathbf{y}$ specifies a point in the algebraic state space $\mathcal{Y}$, which is the space of all algebraic states a power system can adopt. The system variables which are described by algebraic states are for example the complex voltages of network buses or the complex currents over network lines. The algebraic state vector is time-variant and changes depending on the vectors $\mathbf{x}$, $\mathbf{h}$, $\mathbf{u}$, $\mathbf{e}$ and $\mathbf{c}$ following the relationship given by equation 4.13b. The algebraic state vector $\mathbf{y}$ is composed by the vector $\mathbf{v}^{\mathrm{N}}$, whose elements map the nodal complex voltages of the network, and the vector $\hat{\mathbf{y}}$, which maps additional algebraic states:

$$\mathbf{y} = \begin{bmatrix} \mathbf{v}^{\mathrm{N}} \\ \hat{\mathbf{y}} \end{bmatrix} \tag{4.16}$$

Discrete state vector $\mathbf{h}$: The discrete state vector $\mathbf{h}$ describes a point in the discrete state space $\mathcal{H}$, which is the space of all possible discrete state combinations a system can adopt. The discrete state vector

$$\mathbf{h} = [h_1, ..., h_s, ..., h_{n_s}] \tag{4.17}$$

is time-variant and depends on the control signal vector $\mathbf{c}$. Thus, monitoring and control systems can induce changes of single elements of $\mathbf{h}$ by determining new values for the components of $\mathbf{c}$ associated with single discrete states. The single elements of $\mathbf{h}$ model discrete variables such as the tap position of an OLTC transformer or the operation state of a circuit breaker (open or closed).

Power behaviour vector $\mathbf{u}$: The power behaviour vector $\mathbf{u}$ maps the active and reactive power behaviour of all PCUs that belong to the modelled power system as a point in the power behaviour space $\mathcal{U}$.

The power behaviour vector

$$\mathbf{u} = \begin{bmatrix} \mathbf{u}^{\mathrm{CPCU}} \\ \mathbf{u}^{\mathrm{NPCU}} \end{bmatrix} \tag{4.18}$$

is composed of the vector

$$\mathbf{u}^{\mathrm{CPCU}} = [P_1^{\mathrm{CPCU}}, Q_1^{\mathrm{CPCU}}, ..., P_r^{\mathrm{CPCU}}, Q_r^{\mathrm{CPCU}}, ...P_{n_r}^{\mathrm{CPCU}}, Q_{n_r}^{\mathrm{CPCU}}]^{\mathrm{T}}, \tag{4.19}$$

which describes the active and reactive power behaviour of controllable PCUs, and the vector

$$\mathbf{u}^{\mathrm{NPCU}} = [P_1^{\mathrm{NPCU}}, Q_1^{\mathrm{NPCU}}, ..., P_d^{\mathrm{NPCU}}, Q_d^{\mathrm{NPCU}}, ..., P_{n_d}^{\mathrm{NPCU}}, Q_{n_d}^{\mathrm{NPCU}}]^{\mathrm{T}} \tag{4.20}$$

which describes the active and reactive power behaviour of non-controllable PCUs. Here, P_r^{CPCU} is the active and Q_r^{CPCU} the reactive power behaviour of the controllable PCU $r \in R$ and P_d^{NPCU} is the active and Q_d^{NPCU} the reactive power behaviour of the non-controllable PCU $d \in D$.

The active and reactive power behaviour of a NPCU depends on the voltage amplitude of its connection point which is mapped by an element of the algebraic vector $\mathbf{y}$, the dynamic state of the NPCU $\mathbf{x}_d^{\mathrm{NPCU}}$, which is a subvector of $\mathbf{x}$, and relevant external influence factors which are mapped by the vector $\mathbf{e}$. On the other hand, the active and reactive power behaviour of a CPCU additionally depends on the control vector $\mathbf{c}_r^{\mathrm{CPCU}}$ which is a subvector of $\mathbf{c}$ and maps set points issued by a superimposed monitoring and control system which that particular CPCU is requested to follow.

External influencing factors vector e: The external influencing factors vector

$$\mathbf{e} = [e_1, ..., e_e, ..., e_{n_e}] \tag{4.21}$$

maps relevant quantities of the environment which have an impact on the modelled system. External influencing factors are for example the wind speed, solar radiation or temperature at a specific geographical location or variables which model the social behaviour of network participants and have for example an impact on NPCUs.

Monitoring signal vector m: The monitoring signal vector

$$\mathbf{m} = [m_1, ..., m_m, ..., m_{n_m}] \tag{4.22}$$

maps monitoring signals which are obtained by measurement equipment or issued by monitoring and control systems to describe the state of a subsystem which is supervised and controlled by them. The elements of **m** describe for example measured values such as the measured voltage amplitude at a particular network bus or the active and reactive power which flows via a particular network component such a line.

Control signal vector c: The control signal vector

$$\mathbf{c} = [c_1, ..., c_c, ..., c_{n_c}] \tag{4.23}$$

maps control signals which are issued by monitoring and control systems. The elements of **c** map for instance active and reactive power set points of CPCUs, voltage amplitude and frequency set points or set points for the switching position of circuit breakers and OLTC transformers.

4.4.2 Transmission system model

The transmission system model which is a subsystem of the power system model given by equation 4.13 (see also figure 4.1) can be described by the set of non-linear, hybrid differential-algebraic equations

$$\dot{\mathbf{x}}_t^{\mathrm{TN}} = \boldsymbol{f}_t^{\mathrm{TN}}(\mathbf{x}_t^{\mathrm{TN}}, \mathbf{y}_t^{\mathrm{TN}}, \mathbf{h}_t^{\mathrm{TN}}, \mathbf{u}_t^{\mathrm{TN}}, \mathbf{e}_t^{\mathrm{TN}}, \mathbf{c}_t^{\mathrm{TN}}), \tag{4.24a}$$

$$0 = \boldsymbol{g}_t^{\mathrm{TN}}(\mathbf{x}_t^{\mathrm{TN}}, \mathbf{y}_t^{\mathrm{TN}}, \mathbf{h}_t^{\mathrm{TN}}, \mathbf{u}_t^{\mathrm{TN}}, \mathbf{e}_t^{\mathrm{TN}}, \mathbf{c}_t^{\mathrm{TN}}). \tag{4.24b}$$

This set of equations is a subset of the set of equations 4.13. Thus, the vectors $\mathbf{x}_t^{\mathrm{TN}}, \mathbf{y}_t^{\mathrm{TN}}, \mathbf{h}_t^{\mathrm{TN}}, \mathbf{u}_t^{\mathrm{TN}}, \mathbf{e}_t^{\mathrm{TN}}, \mathbf{c}_t^{\mathrm{TN}}$ are subvectors of the vectors which belong to the parameter space of the equation 4.13.

The transmission network model is composed of a monitoring and control system model, a transmission grid model and the models of the PCUs connected to it. Each of these models is represented by a set of differential-algebraic equations which is a subset of the set of equations 4.24. The models of the subsystems which compose the transmission network model are coupled by physical and communication signals. The modelling of transmission network components (power plants, lines, circuit breakers, transformers) in the form of sets of non-linear and hybrid algebraic-differential equations is widely discussed in the literature and is therefore not treated here in detail. In particular, the references [41, 52, 60, 65, 79] have proved among others to be helpful to get into the subject.

4.4.3 Smart Power Cell models

The model of a particular SPC n which is a subsystem of the power system model given by equation 4.13 (see also figure 4.1) can be described by the set of non-linear, hybrid differential-algebraic equations

$$\dot{\mathbf{x}}_n^{\mathrm{SPC}} = \boldsymbol{f}_n^{\mathrm{SPC}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}, \mathbf{h}_n^{\mathrm{SPC}}, \mathbf{u}_n^{\mathrm{SPC}}, \mathbf{e}_n^{\mathrm{SPC}}, \mathbf{c}_n^{\mathrm{SPC}}), \tag{4.25a}$$

$$0 = \boldsymbol{g}_n^{\mathrm{SPC}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}, \mathbf{h}_n^{\mathrm{SPC}}, \mathbf{u}_n^{\mathrm{SPC}}, \mathbf{e}_n^{\mathrm{SPC}}, \mathbf{c}_n^{\mathrm{SPC}}), \tag{4.25b}$$

This set of equations is a subset of the set of equations 4.13. Thus, the vectors $\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}, \mathbf{h}_n^{\mathrm{SPC}}, \mathbf{u}_n^{\mathrm{SPC}}, \mathbf{e}_n^{\mathrm{SPC}}, \mathbf{c}_n^{\mathrm{SPC}}$ are subvectors of the vectors which belong to the parameter space of equation 4.13.

The modelling of single SPC components (distributed generators, storages, loads, lines, circuit breakers, transformers) in the form of sets of non-linear and hybrid algebraic-differential equations is widely discussed in the literature and is therefore not treated here in detail. In particular, the references [7, 60, 65, 93] have proved among others to be helpful to get into the subject.

Each SPC model is composed of a monitoring and control system model, a distribution network model including components such as circuit breakers and OLTC transformers, and a set of PCU models. The models of the subsystems which compose the transmission network model are coupled by physical and communication signals. Each of these models is represented by a set of differential-algebraic equations which is a subset of the set of equations 4.25. An overview of the subsystem models required to model an SPC can be found in [79]. Here, e.g. detailed models of lines, wind energy converters and PV-units are described in the form of algebraic-differential equations. Furthermore, within the context of this dissertation, several related bachelor and master theses were supervised which address e.g. the mathematical modelling of wind energy converters [ST3, ST9], the mathematical modelling of PV-Units [ST10] and the mathematical modelling of other relevant components [ST1, ST7]. Further, a general model for the dynamic representation of PCUs has been described in previous work [DM8].

4.4.4 Monitoring and control system models

The subsystems which compose a future power system organized according to the SPC concept (figure 4.1) are supervised and controlled by MACS. Since the system is hierarchically structured, also the monitoring and control architecture follows a hierarchical organization. Figure 4.2 shows the hierarchical architecture of the monitoring and control system models. As the figure shows, single network components and PCUs are supervised and controlled by MACS at the component level (Level 1). This MACS acquire measurement data from the field and control the behaviour of the single components of the system. The single MACS of level 1 are supervised and controlled by subsystem MACS (Level 2). These MACS ensure that all the components which belong to their corresponding subsystems are operated in a coordinated way. Finally, the single subsystem MACS of level 2 are supervised and controlled by a superimposed MACS which coordinates the behaviour of all subsystems (Transmission network and SPCs) to ensure that the entire system behaves in a secure, stable and efficient manner.

Each MACS is modelled independently and is assigned to a particular subsystem model. The dynamic behaviour of the single MACS can be modelled by non-linear and hybrid systems of algebraic and differential equations whose inputs are the measured signals of their assigned subsystems and outputs the control signals for actuators assigned to them.

$$\dot{\mathbf{x}}_s^{\mathrm{MACS}} = \boldsymbol{f}_s^{\mathrm{MACS}}(\mathbf{x}_s^{\mathrm{MACS}}, \mathbf{y}_s^{\mathrm{MACS}}, \mathbf{h}_s^{\mathrm{MACS}}, \mathbf{e}_s^{\mathrm{MACS}}, \mathbf{m}_s^{\mathrm{MACS}}, \mathbf{c}_s^{\mathrm{MACS}}), \tag{4.26a}$$

$$0 = \boldsymbol{g}_s^{\mathrm{MACS}}(\mathbf{x}_s^{\mathrm{MACS}}, \mathbf{y}_s^{\mathrm{MACS}}, \mathbf{h}_s^{\mathrm{MACS}}, \mathbf{e}_s^{\mathrm{MACS}}, \mathbf{m}_s^{\mathrm{MACS}}, \mathbf{c}_s^{\mathrm{MACS}}). \tag{4.26b}$$

A comprehensive overview of how MACS can be modelled in the form of a set of algebraic and differential equations can be found in [79].

4.4.5 Environment model

In a power system organized according to the SPC concept, the behaviour of many components is directly impacted by the environment. The behaviour of PV units, for instance, depends on the solar radiation and temperature at the geographical location they are installed, the behaviour of wind energy converters depend on the wind speed acting on it and the behaviour of loads vary according to the social behaviour of network users. Thus, the model structure of a future power system organized according to the SPC concept (see figure 4.1) contains an environment model which generates the signals mapped by the external influencing factors vectors $\mathbf{e}^{\mathrm{TS}}$ and $\mathbf{e}_n^{\mathrm{SPC}}$. These vectors are the input of the subsystem models whose behaviour is assumed to be dependent on the environment. The most simple way of representing the environment is to use time

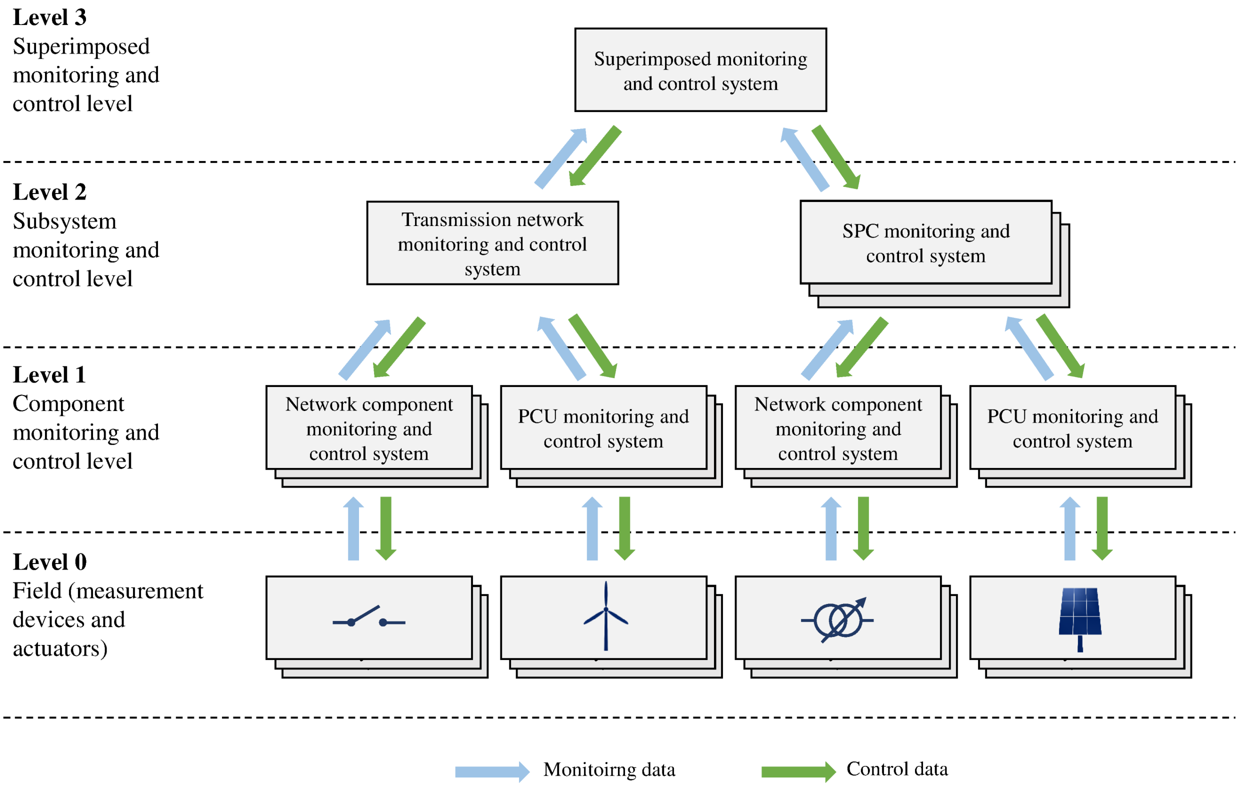


Figure 4.2: Overview of the hierarchical architecture of monitoring and control systems

series of the quantities which are assumed to have an impact on the behaviour of single components of the system. In this case, the output of the environment model is the time series

$$\{\mathbf{e}(t), t = [t_1, t_2, ..., t_n]\} \tag{4.27}$$

On the other hand, if the behaviour of future scenarios needs to be analysed, the environment needs to be modelled using stochastic methods and the output of the environment model is the random process

$$\{\mathbf{E}(t), t =\in [0, \infty]\}. \tag{4.28}$$

In section 5.8.1 the stochastic modelling of the environment in the form of a random process is described.

In this thesis, when dynamic simulations are conducted, time series of quantities describing the environment are used. This is the case in section 6.6 and section 7. Further, in section 5.8 the environment is described as a random process.

4.4.6 Communication model

As stated above, data collected by measurement devices and control signals issued by monitoring and control signals need to be transmitted and processed by means of ICT systems. In literature, several very detailed approaches to model and study the behaviour of ICT systems are described. Besides, many contributions deal with hybrid simulation techniques which are able to simultaneously simulate the ICT and energy systems [DM7]. In this thesis however, a very simplified communication model is used.

The communication model consists of a dead time element of the form

$$\mathbf{y}^{\mathrm{ICT}}(t) = (\mathbf{u}^{\mathrm{ICT}}(t - \mathrm{T}^{\mathrm{Dead}})) \tag{4.29}$$

such that communication delays mapped by the vector $\mathbf{T}^{\mathrm{Dead}}$ can be considered in dynamic simulations. Here, the vector $\mathbf{y}^{\mathrm{ICT}}$ is the output of the communication model and the vector $\mathbf{u}^{\mathrm{ICT}}$ is its input. The elements of the vector $\mathbf{u}^{\mathrm{ICT}}$ map the signals which are sent by measurement devices and monitoring and control systems. The elements of the vector $\mathbf{y}^{\mathrm{ICT}}$ map the signals which are received by actuators and monitoring and control systems.

4.5 Summary

In the previous sections, modelling and simulation techniques to study the behaviour of contemporary and future power systems have been discussed. First in section 4.1 and 4.2 traditional approaches to conduct load flow studies and transient stability studies have been addressed. Then, simplifications were discussed, which are common practice today when conventional power system studies are conducted but are not suitable to study the behaviour of future systems. Finally, in section 4.4, an abstract description of a model which can be used to study the behaviour of future power system is provided. In particular, the model includes detail models of the transmission and distribution network systems enabling the representation of interactions across voltage levels. Furthermore, the model also comprises models of the monitoring and control systems, enabling the consideration of the interactions of the physical infrastructure with the monitoring and control domain. To this, also a simple communication model is considered. Last but not least, an environment model is part of the future power system model in order to consider the impact of external influencing factors such as the weather.

A specific implementation of a future power system modelled as proposed in section 4.4 is described in chapter 7.

5 The flexibility of a Smart Power Cell to support the operation of the transmission network

In chapter 3, a system architecture and operational concept for a future power system has been presented. The concept is founded on the idea of organizing the distribution network level of a future power system in supervised and controlled grid subsections called SPCs which are connected to particular buses of the transmission network via OLTC transformers. The behaviour of SPCs is supervised and controlled by a superimposed monitoring and control system which coordinates their behaviour in such a way that the entire system can be operated in a secure, stable and efficient way.

The superimposed monitoring and control system of a future power system organized following the SPC concept can influence the behaviour of SPCs in several ways (see e.g. section 3.4). This chapter, however, focuses on the IPF control and describes in this context two methods to determine the range (hereinafter also referred to as flexibility) in which the IPF of an SPC can be adjusted to participate in the operation of the transmission network. The information regarding the flexibility of an SPC can be used by a TSO to plan in advance in what extent each SPC connected to its responsibility area will participate in the operation of the system (e.g. congestion management, balancing services or system optimization) by adjusting its IPF.

Method 1, which is described in section 5.7, can be used to determine the flexibility of an SPC under the premise of perfect information, i.e. when all modelled influencing factors are known. Method 2, on the other hand, is meant to be used to estimate in advance the flexibility that an SPC will have in future time intervals using forecasts of time-variant influencing factors under consideration of uncertainty by a probabilistic approach. This method is described in section 5.8.3. In order to describe the developed methods, some terms and concepts need to be introduced and explained. This is done in the remaining sections of the chapter. Finally, selected results of conducted case studies are presented in section 5.9 in order to demonstrate the developed methods.

A preliminary method for describing the flexibility of an SPC to support the operation of the transmission network was described in [DM11]. Subsequently, relevant investigations were carried out in cooperation with students of the TU Dortmund University within the framework of bachelor and master theses [ST2, ST5, ST6]. Finally, the methods described in this chapter were developed in collaboration with the author of [ST4] and published in [DM10].

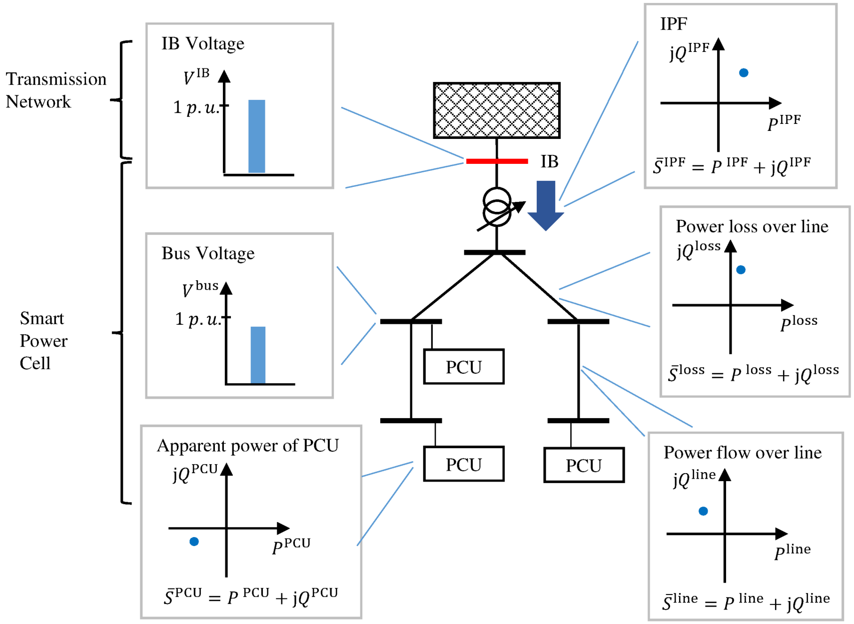


Figure 5.1: Schematic overview of the main quantities which describe the operating point of the electric grid of an SPC

5.1 Flexibility of a Smart Power Cell to control its Interconnection Power Flow

As has been discussed in section 3.7, the IPF of an SPC at a specific moment in time $t = t^*$ can be visually represented as a point in the complex P-Q plane. This point describes the active and reactive power that an SPC exchanges with the transmission network at a given moment. The IPF of an SPC at a particular moment in time $t = t^*$ depends on its operating state which in turn depends on the operating state of all its components: PCUs, buses, lines, circuit breakers, OLTC transformers. This is suggested by figure 5.1 which gives a schematic overview of the main quantities which describe the operating state of the electric grid of an SPC and the operating state of its components.

The characterization of the flexibility of an SPC to adapt its IPF to support the operation of the transmission network requires a description of the relationship between the behaviour of the components of the SPC and its IPF. This relationship - which can be described by the classic steady-state model of an electric grid used in load flow analysis (see section 4.1) - can be derived from the dynamic model of a smart power cell and be described by a set of non-linear algebraic equations:

$$0 = \boldsymbol{g}^{\mathrm{SPC}}(\mathbf{s}^{\mathrm{N}}, \mathbf{v}^{\mathrm{N}}, \mathbf{Y}^{\mathrm{N}}(\mathbf{h}^{\mathrm{SPC}}), \mathbf{u}^{\mathrm{CPCU}}, \mathbf{u}^{\mathrm{NPCU}}, \bar{V}^{\mathrm{IB}}, \mathbf{s}^{\mathrm{line,s}}, \mathbf{s}^{\mathrm{line,r}}, \mathbf{s}^{\mathrm{loss}}, \bar{S}^{\mathrm{IPF}}) \quad (5.1)$$

Here,

- $\mathbf{s}^{\mathrm{N}}$ is a vector which maps the nodal apparent powers of the grid of the studied SPC,
- $\mathbf{v}^{\mathrm{N}}$ is a vector which maps the complex nodal voltages of the grid of the studied SPC,
- $\mathbf{Y}^{\mathrm{N}}$ is the nodal admittance matrix which describes the electric characteristics of the electric grid of the studied SPC,
- $\mathbf{h}^{\mathrm{SPC}}$ is a vector which describes the discrete states of the Discrete Switching Components (DSC) such as circuit breakers and OLTC transformers belonging to the studied SPC,
- $\mathbf{u}^{\mathrm{CPCU}}$ is a vector which maps the active and reactive power behaviour of controllable PCUs connected within the studied SPC,
- $\mathbf{u}^{\mathrm{NPCU}}$ is a vector which maps the active and reactive power behaviour of non controllable PCUs connected within the studied SPC,
- $\bar{V}^{\mathrm{IB}}$ is the complex voltage of the interconnection bus which interconnects the transmission network with the studied SPC,
- $\mathbf{s}^{\mathrm{line,s}}$ is a vector which maps the apparent load flows at the sending end of the lines which belong to the grid of the studied SPC,
- $\mathbf{s}^{\mathrm{line,r}}$ is a vector which maps the apparent load flows at the receiving end of the lines belonging to the grid of the studied SPC,
- $\mathbf{s}^{\mathrm{loss}}$ is the vector which maps the apparent power losses over the lines belonging to the grid of the studied SPC and
- $\bar{S}^{\mathrm{IPF}}$ is the apparent IPF which flows from the interconnection bus into the modelled SPC.

If the values of the vectors

$$\mathbf{u}^{\mathrm{CPCU}}, \mathbf{u}^{\mathrm{NPCU}}, \mathbf{h}^{\mathrm{SPC}}, \bar{V}^{\mathrm{IB}}$$

are given, the system of equations 5.1 can be used to determine the corresponding operating point

$$\mathbf{p}_n^{\mathrm{SPC}} = [\mathbf{s}^{\mathrm{N}}, \mathbf{v}^{\mathrm{N}}, \mathbf{h}^{\mathrm{SPC}}, \mathbf{u}^{\mathrm{CPCU}}, \mathbf{u}^{\mathrm{NPCU}}, \bar{V}^{\mathrm{IB}}, \mathbf{s}^{\mathrm{line,s}}, \mathbf{s}^{\mathrm{line,r}}, \mathbf{s}^{\mathrm{loss}}, \bar{S}^{\mathrm{IPF}}]^{\mathrm{T}} \tag{5.2}$$

which fully describes the steady state of the electric grid of the studied SPC n. Note that $\mathbf{p}_n^{\mathrm{SPC}}$ is a column vector composed of the subvectors $\mathbf{s}^{\mathrm{N}}, \mathbf{v}^{\mathrm{N}}, ..., \bar{S}^{\mathrm{IPF}}$. For simplicity, however, the required transpose operators (e.g. $\mathbf{s}^T$) after each vector are not displayed here.

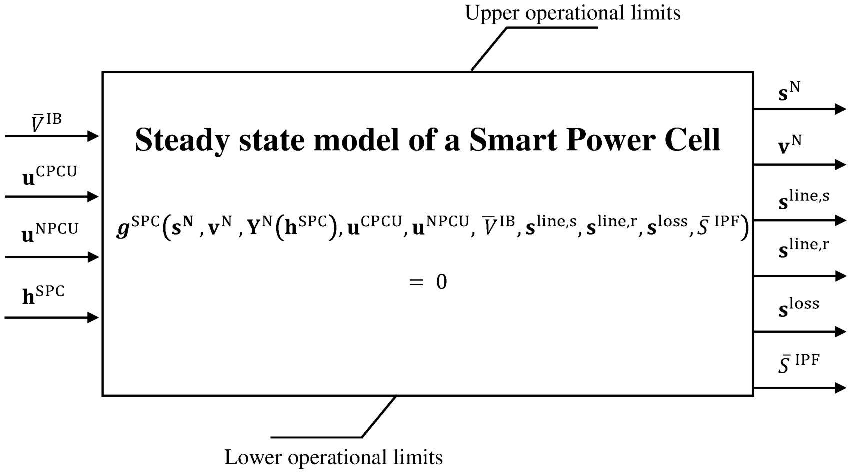


Figure 5.2: Overview of inputs and outputs of the steady-state model of the electric grid of a smart power cell used for the computation of IPFs

The model described by equation 5.1 can be thought of as a system with inputs and outputs as figure 5.2 shows. Figure 5.2 suggests that the IPF of an SPC is a function of the voltage of its interconnection bus $\bar{V}^{\mathrm{IB}}$, the active and reactive power behaviour of its controllable and non-controllable PCUs ($\mathbf{u}^{\mathrm{CPCU}}, \mathbf{u}^{\mathrm{NPCU}}$) and the switching state ($\mathbf{h}^{\mathrm{SPC}}$) of its Discrete Switching Components (DSCs) such as circuit breakers and OLTC transformers. According to this model, any change of the input values $\mathbf{u}^{\mathrm{CPCU}}, \mathbf{u}^{\mathrm{NPCU}}, \mathbf{h}^{\mathrm{SPC}}, \bar{V}^{\mathrm{IB}}$ leads to a change of the operating point $\mathbf{p}_n^{\mathrm{SPC}}$ of the modelled electric grid and thus also to a change of its IPF $\bar{S}^{\mathrm{IPF}}$.

By a suitable control scheme, the behaviour of controllable PCUs ($\mathbf{u}^{\mathrm{CPCU}}$) and the switching state of circuit breakers and OLTC transformers ($\mathbf{h}^{\mathrm{SPC}}$) belonging to an SPC can be controlled to adjust its IPF according to pre-established

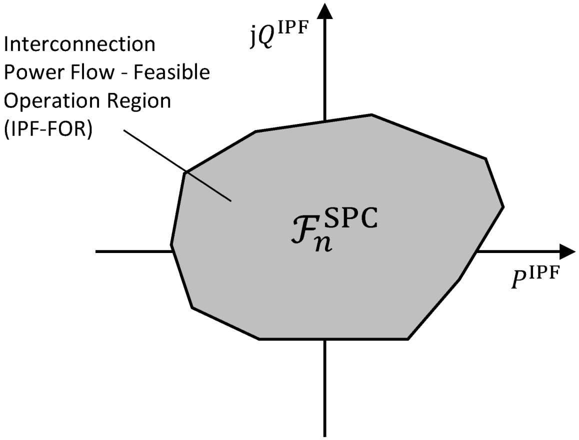


Figure 5.3: Interconnection Power Flow Feasible Operation Region (IPF-FOR): Description of the flexibility of an SPC to adjust its IPF by a shape in the complex P-Q-plane

reference values. A control scheme to control the IPF of an SPC is discussed in section 6.

The flexibility of PCUs to adjust their active and reactive power behaviour is limited and changes in their power behaviour can lead to violations of operational grid constraints. Thus, the range in which an SPC can adjust its apparent IPF to support the operation of the transmission network is restricted to a particular region of the P-Q-plane. In order to involve SPCs in the operation of transmission systems by controlling their IPF, information regarding the available flexibility to adapt their behaviour is required. In the following, the range in which an SPC can adjust its IPF to support the operation of the transmission network will be referred to as IPF Feasible Operation Region (FOR) and will be denoted by $\mathcal{F}_n^{\text{SPC}} \in \mathbb{C}$.

Definition 3 (IPF-FOR)**.** *The IPF-FOR of an SPC is the set of feasible IPFs* $\mathcal{F}^{\text{SPC}} = \{\bar{S}_1^{\text{IPF}}, \bar{S}_2^{\text{IPF}}, ...\} \subseteq \mathbb{C}$ *which can be achieved by a suitable control of controllable PCUs (*$\mathbf{u}^{\text{CPCU}}$*) and switching devices (*$\mathbf{h}^{\text{SPC}}$*) without transgressing operational limits, e.g. voltage and line loading limits.*

The IPF-FOR describes the flexibility of an SPC for IPF control and can graphically be represented by a shape in the complex P-Q-plane as Fig. 5.3 shows, e.g. by a polygon. This shape represents the set of possible IPFs which an SPC can adopt by a suitable control of its components provided that no operational limit is violated.

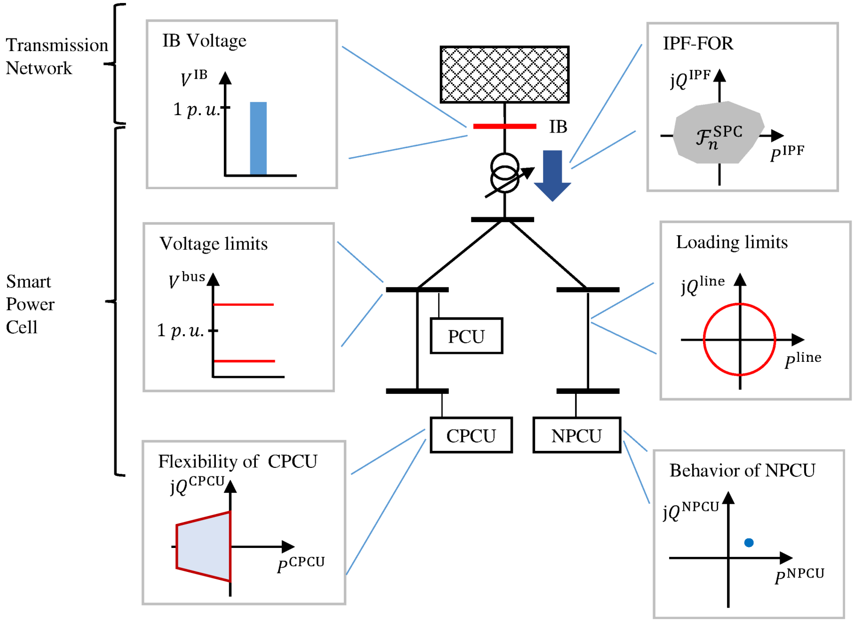


Figure 5.4: Schematic overview of the dependency of the IPF-FOR of an SPC on the behaviour of its components and its operational constraints

The IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ of a particular SPC depends on (i) the voltage amplitude of its interconnection bus, (ii) the operational limits of its electric grid (e.g. voltage and line loading limits), (iii) the time variant active and reactive power behaviour of its non-controllable PCUs and (iv) the time variant flexibility of its controllable PCUs. A schematic overview of the dependency of the IPF-FOR of an SPC on its operational constraints and the operational space of its components is depicted in figure 5.4.

5.2 Flexibility of Controllable Power Conversion Units to participate in the Interconnection Power Flow control of a Smart Power Cell

The flexibility of a controllable PCU to adjust its active and reactive power behaviour according to setpoints provided by a superimposed monitoring and control system can be described with a shape in the complex P-Q-plane. This shape, which in the following will be referred to as PCU-FOR and will be denoted by $\mathcal{F}_r^{\mathrm{PCU}}$, represents the set of all possible operation points and the associated apparent power behaviours that a particular controllable PCU r can adopt at a given moment. The shape of the PCU-FOR of a particular PCU depends on the physical properties of the PCU (e.g. maximum loading capability of its power electronic converter) and on external determinants which have an impact on the behaviour of the PCU (e.g. wind speed, solar radiation, temperature, the social behaviour of network users).

To model the PCU-FOR of different PCUs, different shape types are required. Figure 5.5 shows some examples of PCU-FORs.

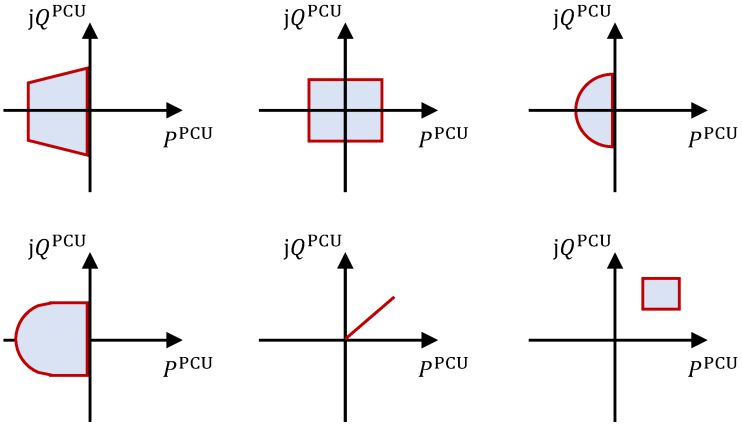


Figure 5.5: Exemplary PCU-FOR types associated with different types of PCUs

The PCU-FOR of a particular PCU can be described by a set of non-linear inequality equations of the form

$$\mathbf{l}_r^{\min}(\mathbf{e}_r^{\mathrm{PCU}}) \leq \boldsymbol{f}_r^{\mathrm{lim,FOR}}(\mathbf{p}_r^{\mathrm{PCU}}) \leq \mathbf{l}_r^{\max}(\mathbf{e}_r^{\mathrm{PCU}}). \tag{5.3}$$

Here, $\mathbf{l}_r^{\min}$ and $\mathbf{l}_r^{\max}$ are vectors that define limits which partially depend on particular external influencing factors which are mapped by the vector $\mathbf{e}_r^{\mathrm{PCU}}$. Further, $\mathbf{f}_r^{\mathrm{lim,FOR}}$ is a non-linear function of the operating point $\mathbf{p}_r^{\mathrm{PCU}}$ of the PCU r. Note that the value of the vector $\mathbf{e}_r^{\mathrm{PCU}}$, which maps external influencing factors such as the wind speed, the solar radiation or the social behaviour of network participants, is time variant. Thus the PCU-FOR $\mathcal{F}_r^{\mathrm{PCU}}$ needs to be considered to be time variant as well.

In the next subsection the description of the PCU-FOR of the following types of controllable PCUs is given: Distributed generators, storage devices and flexible loads.

5.2.1 Flexibility of a distributed generator to participate in the Interconnection Power Flow control of a Smart Power Cell

In this section, the definition of the PCU-FOR of a distributed generator that can be modelled with the model depicted in figure 5.6 is described.

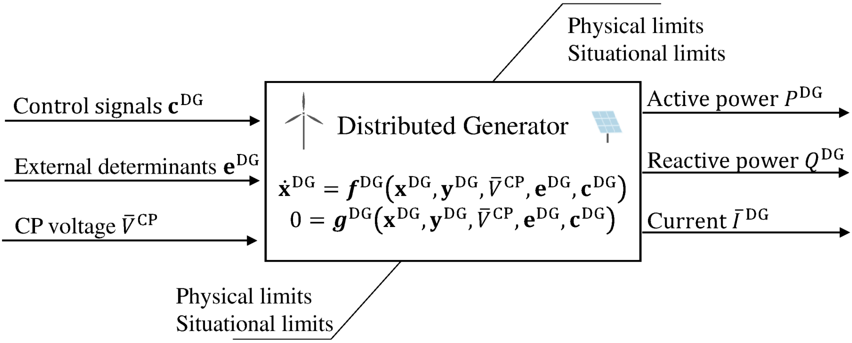


Figure 5.6: Block diagram of the model of a controllable distributed generator as an example of a controllable PCU

The flexibility of such a generator can be described by its PCU-FOR which is a shape in the P-Q-plane as the one illustrated in figure 5.7. The light blue area represents the PCU-FOR of the modelled unit. This area is defined by the following inequality equations:

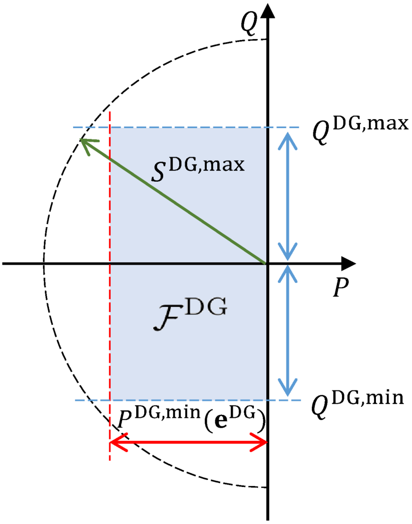


Figure 5.7: PCU-FOR: Description of the flexibility of a distributed generator to participate in the IPF control of an SPC

$$|P^{\text{DG}}(t)| \leq S^{\text{DG,max}} \tag{5.4}$$

$$Q^{\text{DG,min}} \leq Q^{\text{DG}}(t) \leq Q^{\text{DG,max}} \tag{5.5}$$

$$Q^{\text{DG}}(t) \leq \sqrt{(S^{\text{DG,max}})^2 - (P^{\text{DG}}(t))^2} \tag{5.6}$$

$$P^{\text{DG,min}}(\mathbf{e}^{\text{DG}}) \leq P^{\text{DG}}(t) \leq P^{\text{DG,max}}(\mathbf{e}^{\text{DG}}) \tag{5.7}$$

Here, $S^{\text{DG,max}}$ is the maximum apparent power the DG can feed into the network. $Q^{\text{DG,max}}$ and $Q^{\text{DG,min}}$ are maximum and minimum reactive power limits which can be additionally considered. $P^{\text{DG,max}}(\mathbf{e}^{\text{DG}})$ and $P^{\text{DG,min}}(\mathbf{e}^{\text{DG}})$ are active power limits. Note that $P^{\text{DG,max}}(\mathbf{e}^{\text{DG}})$ and $P^{\text{DG,min}}(\mathbf{e}^{\text{DG}})$ depend on the external determinants vector $\mathbf{e}^{\text{DG}}$ which varies over time.

The PCU-FOR illustrated in figure 5.7 describes the flexibility of a PCU at a given point in time t^* depending on the associated scenario of external determinants $\mathbf{e}^{\text{DG}}(t^*)$. The quantities described by the vector $\mathbf{e}^{\text{DG}}$, however, are time

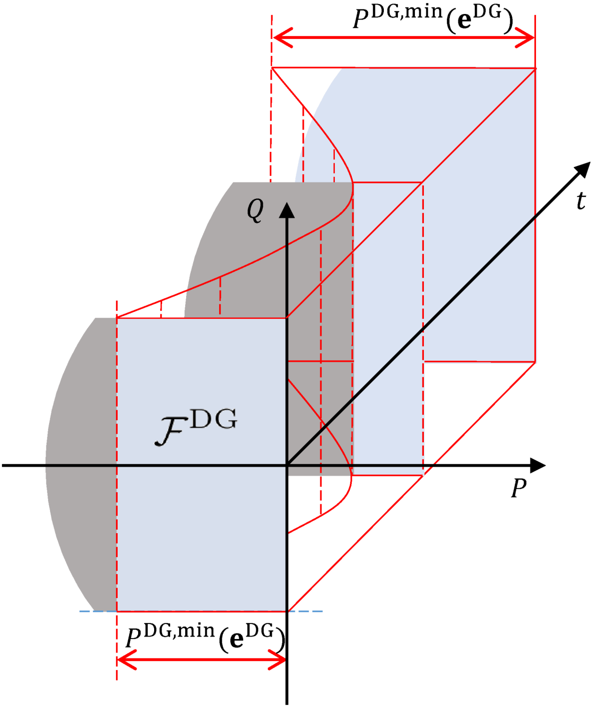


Figure 5.8: Evolution over time of the PCU-FOR of a DG during the time interval $t^0 \leq t \leq t^{\mathrm{end}}$

variant and therefore, if the trajectory of $\mathbf{e}^{\mathrm{DG}}$ for a time interval $t^0 \leq t \leq t^{\mathrm{end}}$ is considered, the evolution of the PCU-FOR over time can be described. This is schematically depicted in figure 5.8.

5.2.2 Flexibility of a storage device to participate in the Interconnection Power Flow control of a Smart Power Cell

This sections addresses the definition of the PCU-FOR of a storage device. A storage device can be modelled with the model depicted in figure 5.9.

A storage device connected to an SPC is a PCU that can inject or withdraw apparent power into or from the electric grid. Its flexibility to adjust its active power in a predefined time interval $t^0 \leq t \leq t^{\mathrm{end}}$, under the premise that it has

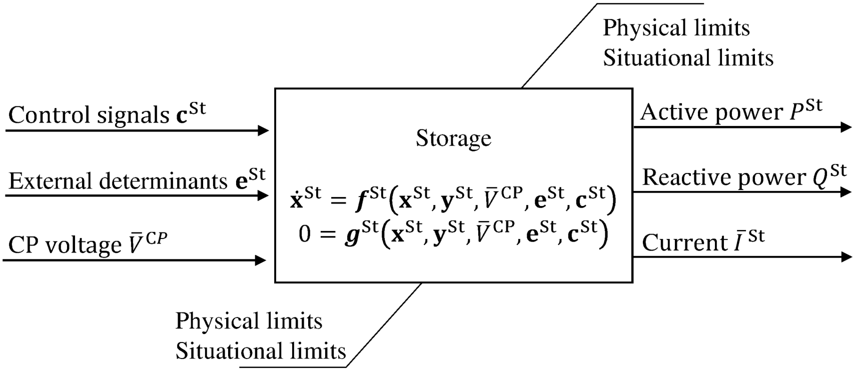


Figure 5.9: Block diagram of the model of a controllable storage device as an example of a controllable PCU

to inject a constant power during the complete interval, depends on its state of charge $x^{\mathrm{St,charge}}(t^0)$. When its state of charge is known and a time interval $t^0 \leq t \leq t^{\mathrm{end}}$ is predetermined, the maximum and minimum active power a storage device can continuously inject into or withdraw from the grid can be determined. Based on this information the PCU-FOR of a storage device for that initial state of charge and time interval can be determined.

The PCU-FOR of a storage device for a time interval $t^0 \leq t \leq t^{\mathrm{end}}$ and a known initial state of charge can be illustrated as depicted in Fig. 5.10. The light blue area of Fig. 5.10 embodies the PCU-FOR of an exemplary storage unit.

The PCU-FOR of a storage device can be described using the following equations:

$$|P^{\mathrm{St}}(t)| \leq S^{\mathrm{St,max}} \tag{5.8}$$

$$Q^{\mathrm{St,min}} \leq Q^{\mathrm{St}}(t) \leq Q^{\mathrm{St,max}} \tag{5.9}$$

$$Q^{\mathrm{St}} \leq \sqrt{(S^{\mathrm{St,max}})^2 - (P^{\mathrm{St}}(t))^2} \tag{5.10}$$

$$P^{\mathrm{St,min}}(\mathbf{x}^{\mathrm{St}}, \mathbf{e}^{\mathrm{St}}) \leq P^{\mathrm{St}}(t) \leq P^{\mathrm{St,max}}(\mathbf{x}^{\mathrm{St}}, \mathbf{e}^{\mathrm{St}}) \tag{5.11}$$

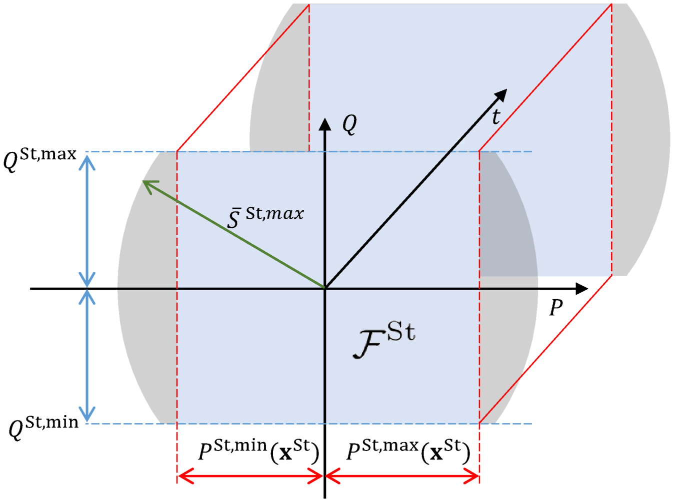


Figure 5.10: Evolution over time of the PCU-FOR of a storage device during the time interval $t^0 \leq t \leq t^{\mathrm{end}}$

5.2.3 Flexibility of a flexible load to participate in the Interconnection Power Flow control of a Smart Power Cell

Flexible loads, which can be modelled as depicted in Fig. 5.11, are PCUs that can adapt their power consumption during a predetermined time interval to follow reference values.

Thus, their active and reactive power trajectory can be adapted to support the network operation. The PCU-FOR of a flexible load depends on the external determinant vector $\mathbf{e}^{\mathrm{Fl}}$ (e.g. social behaviour, industrial processes, automatic load cycles, etc.) and can be described with the following equations:

$$P^{\mathrm{Fl,min}}(\mathbf{e}^{\mathrm{Fl}}) \leq P^{\mathrm{Fl}}(t) \leq P^{\mathrm{Fl,max}}(\mathbf{e}^{\mathrm{Fl}}) \tag{5.12}$$

$$Q^{\mathrm{Fl,min}}(\mathbf{e}^{\mathrm{Fl}}) \leq Q^{\mathrm{Fl}}(t) \leq Q^{\mathrm{Fl,max}}(\mathbf{e}^{\mathrm{Fl}}) \tag{5.13}$$

Fig. 5.12 depicts the evolution of the PCU-FOR of a flexible load over time.

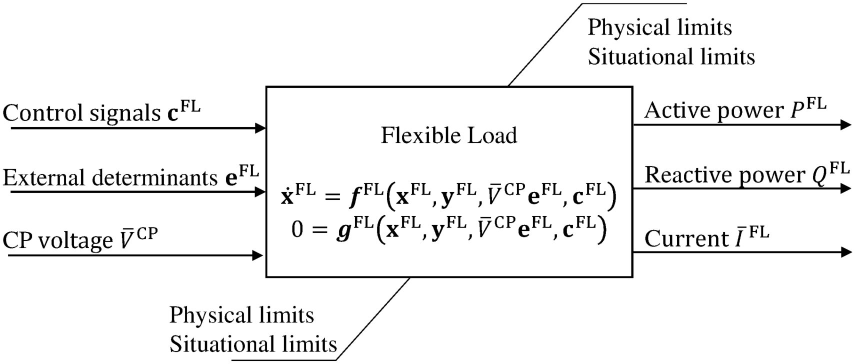


Figure 5.11: Block diagram of the model of a flexible load as an example of a controllable PCU

5.2.4 Condensed description of the FORs of controllable power conversion units connected to a particular Smart Power Cell

In the previous sections, the description of the FORs of single PCUs has been discussed. In this section, a set is defined which contains all the FORs of the controllable PCUs connected to a particular SPC n. This set is used in the sections 5.6 and 5.8 in order to simplify the description of the developed methods.

Consider a particular SPC n with n_r controllable PCUs. The flexibility of each PCU $r \in R_n$ under consideration of a particular scenario of external conditions $\mathbf{e}_n^{\mathrm{SPC}}(t)$ at a particular moment in time $t = t^*$ can be described with its corresponding FOR by the set $\mathcal{F}_r^{\mathrm{PCU}}$. If this is done for all PCUs $r \in R_n$ which belong to the SPC n, we obtain a set of FORs of the length n_r:

$$\mathcal{M}_n^{\mathrm{PCU-FOR}}(\mathbf{e}^{\mathrm{SPC}}) = \{\mathcal{F}_1^{\mathrm{PCU}}(\mathbf{e}^{\mathrm{SPC}}), ..., \mathcal{F}_r^{\mathrm{PCU}}(\mathbf{e}^{\mathrm{SPC}}), ..., \mathcal{F}_{n_r}^{\mathrm{PCU}}(\mathbf{e}^{\mathrm{SPC}})\} \quad (5.14)$$

This set describes the flexibility of all controllable PCUs connected to the SPC n.

Here, it is important to note that $\mathcal{M}_n^{\mathrm{PCU-FOR}}(\mathbf{e}^{\mathrm{SPC}})$ is a function of the external condition vector $\mathbf{e}^{\mathrm{SPC}}$ which varies over time since it describes external stochastic quantities such as the wind speed, solar radiation, social behaviour or temperature acting on the SPC n. Thus, for different values of $\mathbf{e}^{\mathrm{SPC}}(t)$ different sets $\mathcal{M}_n^{\mathrm{PCU-FOR}}(\mathbf{e}^{\mathrm{SPC}})$ are obtained. This fact is important to understand why the flexibility of an SPC varies over time, as is explained in section 5.7.

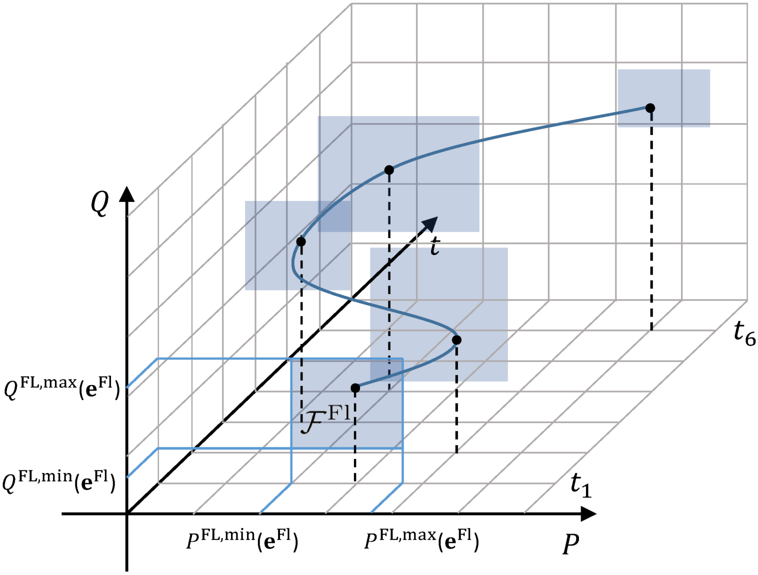


Figure 5.12: Evolution of the PCU-FOR of a flexible load over time

5.3 Impact of non-controllable Power Conversion Units on the IPF-FOR

The behaviour of non-controllable PCUs cannot be coordinated by a monitoring and control system to support the operation of the grid. However, their behaviour does have a critical impact on the trajectory of the IPF of an SPC. Thus, although these units do not provide operational flexibility (the area of their PCU-FOR is zero) they need to be considered when the IPF-FOR of an SPC is determined. In particular, interactions between these units and the grid cannot be neglected. These interactions occur due to the fact that the behaviour of many of these units is voltage-dependent.

The dynamic behaviour of a non-controllable PCU can be described by a model as the one illustrated in Fig. 5.13.

As figure 5.13 shows, the behaviour of a non-controllable PCU depends on the voltage amplitude of its connection point $\bar{V}^{\mathrm{CP}}$ and the external influencing factors which have an impact on the modelled unit and are mapped by the vector $\mathbf{e}^{\mathrm{NPCU}}$. Thus, for a particular trajectory of $\mathbf{e}^{\mathrm{NPCU}}(t)$ for $t = [t^0, t^{\mathrm{end}}]$, two differ-

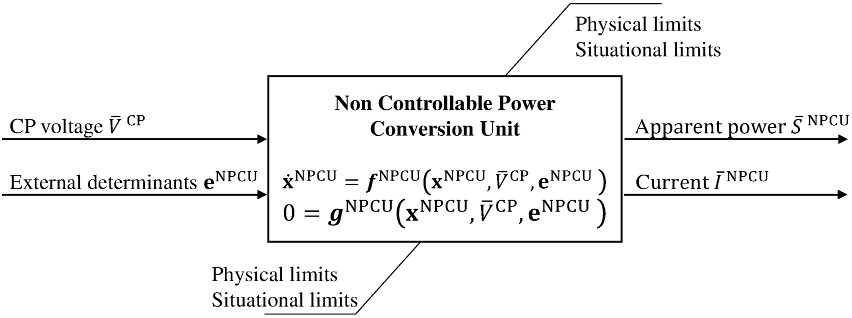


Figure 5.13: Block diagram of the model of a Non Controllable PCU

ent trajectories $\bar{S}^{\mathrm{NPCU}}(t)$ may result if two different trajectories of $\bar{V}^{\mathrm{CP}}(t)$ are considered.

This is depicted in Fig. 5.14 which shows the active and reactive power behaviour of a NPCU over a time interval for the same trajectory of $\mathbf{e}^{\mathrm{NPCU}}$ but for two different trajectories of $\bar{V}^{\mathrm{CP}}$.

Frequently, this fact is referred to in the literature as the voltage dependency of loads which means that the active and reactive power consumption of non-controllable loads not only depends on external influencing factors but also on the state of the electric grid.

In the context of IPF control of SPCs this fact is important since changes in the active and reactive power behaviour of controllable PCUs also have an impact on the voltage profile of the grid. Thus, when the behaviour of controllable PCUs is changed, also the active and reactive behaviour of non-controllable PCUs is affected which also has an impact on the IPF of the SPC.

5.4 Impact of Discrete Switching Components such as OLTC transformers and circuit breakers on the IPF-FOR

As figure 5.2 shows, the nodal admittance matrix $\mathbf{Y}^{\mathrm{N}}(\mathbf{h}^{\mathrm{SPC}})$ is a function of the vector $\mathbf{h}^{\mathrm{SPC}}$. This vector describes the discrete states of the Discrete Switching Components (DSC) that belong to the studied SPC. DSCs are for example OLTC transformers and circuit breakers. Each element of the vector $\mathbf{h}^{\mathrm{SPC}}$ is associated with a discrete state of a DSC. When the value of $\mathbf{h}^{\mathrm{SPC}}$ changes, this also leads

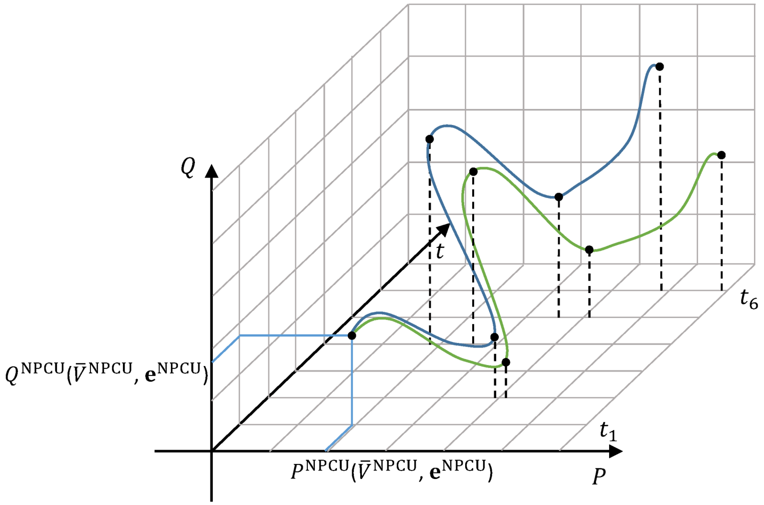


Figure 5.14: Trajectories of the active and reactive power behaviour of a non-controllable PCU depending on two different voltage trajectories of its connection point

to a change of the value of $\mathbf{Y}^{\mathrm{N}}(\mathbf{h}^{\mathrm{SPC}})$ and thus, also the IPF $\bar{S}^{\mathrm{IPF}}$ of the SPC is impacted. Thus, the flexibility of an SPC and therefore also its IPF-FOR depends on all possible values which $\mathbf{h}^{\mathrm{SPC}}$ can take.

The flexibility of a single DSC can be described by the set of all possible discrete states that the unit can adopt. In this thesis, this set is called DSC-FOR and is denoted by $\mathcal{F}_w^{\mathrm{DSC}}$. For example, the FOR of a particular circuit breaker w^* can be defined as

$$\mathcal{F}_{w^*}^{\mathrm{DSC}} = \{1, 0\}. \tag{5.15}$$

In this case, the corresponding element h_{w^*} of $\mathbf{h}^{\mathrm{SPC}}$ can either take the value $h_{w^*} = 1$ if the corresponding circuit breaker w^* is closed or $h_{w^*} = 0$ if the corresponding circuit breaker w^* is open.

In order to describe the flexibility of all the DSC which belong to a particular SPC n in a condensed way, the set

$$\mathcal{M}_n^{\mathrm{DSC-FOR}} = \{\mathcal{F}_1^{\mathrm{DSC}}, ..., \mathcal{F}_w^{\mathrm{DSC}}, ..., \mathcal{F}_{n_w}^{\mathrm{DSC}}\}. \tag{5.16}$$

can be used.

This set contains the FORs of all the DSCs $w \in W_n$ which belong to the SPC n

and defines the discrete space spanned by the vector $\mathbf{h}^{\mathrm{SPC}}$. Note that $\mathcal{M}_n^{\mathrm{DSC-FOR}}$ does not depend on external conditions and therefore remains constant over time. Thus, it can be considered to be time-invariant.

5.5 Restriction of the feasible operational region of the electric grid of Smart Power Cell due to operational constraints

In order to enforce a secure and stable operation of an SPC, the trajectory of its operating point $\mathbf{p}^{\mathrm{SPC}} \in \mathcal{P}^{\mathrm{SPC}}$ is restricted to a particular subset $\mathcal{P}^{\mathrm{SPC,Feasible}}$ of its operational space $\mathcal{P}^{\mathrm{SPC}}$. Only if the operating point $\mathbf{p}^{\mathrm{SPC}}$ is located within the feasible operational space $\mathcal{P}^{\mathrm{SPC,Feasible}}$, it can be considered as secure. The feasible operational space of an SPC is among others determined by the operational constraints of its electric grid. Operational constraints are for example bus voltage magnitude limits and thermal restrictions. In the following, operational constraints related to the voltage and thermal limits of the electric grid of an SPC are described.

5.5.1 Voltage constraints

The vector $\mathbf{v}^{\mathrm{N}}$ which spans the space $\mathcal{V}^{\mathrm{SPC}}$ maps the complex voltages of the buses of the electric grid of an SPC. Due to security and supply quality concerns, the value of $\mathbf{v}^{\mathrm{N}}$ is required to stay within a restricted subspace of $\mathcal{V}^{\mathrm{SPC}}$ that in the following will be denoted by $\mathcal{V}^{\mathrm{SPC,Feasible}}$. This space describes the range of feasible voltages which the buses of an SPC can adopt and are considered to be secure. $\mathcal{V}^{\mathrm{SPC,Feasible}}$ can e.g. be defined by the following set of equations:

$$\mathbf{v}^{\mathrm{N,amp,min}} \leq |\mathbf{v}^{\mathrm{N}}| \leq \mathbf{v}^{\mathrm{N,amp,max}} \tag{5.17}$$

Here, $\mathbf{v}^{\mathrm{N,amp,min}}$ and $\mathbf{v}^{\mathrm{N,amp,max}}$ are the upper and lower voltage amplitude limits respectively.

5.5.2 Thermal restrictions

The vectors $\mathbf{s}^{\mathrm{line,s}}$ and $\mathbf{s}^{\mathrm{line,r}}$, which together span the space $\mathcal{S}^{\mathrm{line}}$, map the apparent power flows over the lines of an SPC. Due to security concerns, the values of $\mathbf{s}^{\mathrm{line,s}}$ and $\mathbf{s}^{\mathrm{line,r}}$ are required to stay within a restricted subspace of

$\mathcal{S}^{\mathrm{SPC,line}}$ that in the following will be denoted by $\mathcal{S}^{\mathrm{SPC,line,Feasible}}$. This space can be described with the following set of inequality equations:

$$|\mathbf{s}^{\mathrm{line,s}}| \leq \mathbf{s}^{\mathrm{line,max}} \tag{5.18}$$

$$|\mathbf{s}^{\mathrm{line,r}}| \leq \mathbf{s}^{\mathrm{line,max}} \tag{5.19}$$

5.6 Determination of the IPF-FOR of a Smart Power Cell for a specific moment in time (Method 1)

This section describes the developed method to approximate the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ of a particular SPC n for a known scenario of external influencing factors $\mathbf{e}^{\mathrm{SPC}}(t)$ at a particular point in time $t = t^*$. An overview of the developed method which is structured in four processing steps (PS1 - PS4) is depicted in Fig. 5.15.

The method requires a mathematical model of the electric grid of the studied SPC (see section 5.1). Further, the following data need to be defined:

(i) The values of influencing factors which can not be directly controlled such as the interconnection voltage $\bar{V}_n^{\mathrm{IB}}$ and the active and reactive power behaviour of non-controllable PCUs $\mathbf{u}_n^{\mathrm{NPCU}}(\mathbf{e}^{\mathrm{SPC}})$ at $t = t^*$,

(ii) the set $\mathcal{M}_n^{\mathrm{PCU-FOR}}(\mathbf{e}^{\mathrm{SPC}})$ at $t = t^*$ which contains the FORs $\mathcal{F}_r^{\mathrm{PCU}}$ of all controllable PCUs $r \in R_n$ which belong to the studied SPC n,

(iii) the set $\mathcal{M}_n^{\mathrm{DSC-FOR}}$ which contains the FORs $\mathcal{F}_w^{\mathrm{DSC}}$ of all DSCs $w \in W_n$ which belong to the SPC n,

(iv) the operational limits $\mathbf{v}^{\mathrm{N,amp,min}}$, $\mathbf{v}^{\mathrm{N,amp,max}}$ and $\mathbf{s}^{\mathrm{line,max}}$ which restrict the operational region of the electric grid of the studied SPC.

As the figure 5.15 shows, the input data required for the method can be classified into two groups: time-variant and time-invariant input data. Time-variant input data is scenario dependent and varies over time. The inputs which are time-variant are the set $\mathcal{M}_n^{\mathrm{PCU-FOR}}(\mathbf{e}^{\mathrm{SPC}})$ which describes the flexibility of the PCUs connected to the studied SPC, the vector $\mathbf{u}_n^{\mathrm{NPCU}}$ which describes the active and reactive power behaviour of non-controllable PCU and the interconnection voltage $\bar{V}_n^{\mathrm{IB}}$ which describes the voltage at the interconnection bus that interlinks the SPC n with the transmission network. Both, the vector $\mathbf{u}_n^{\mathrm{NPCU}}$ and the set $\mathcal{M}_n^{\mathrm{PCU-FOR}}(\mathbf{e}^{\mathrm{SPC}})$ depend on the external influencing factors which are mapped by the vector $\mathbf{e}^{\mathrm{SPC}}$ and vary over time. Further, the interconnection voltage $\bar{V}_n^{\mathrm{IB}}$

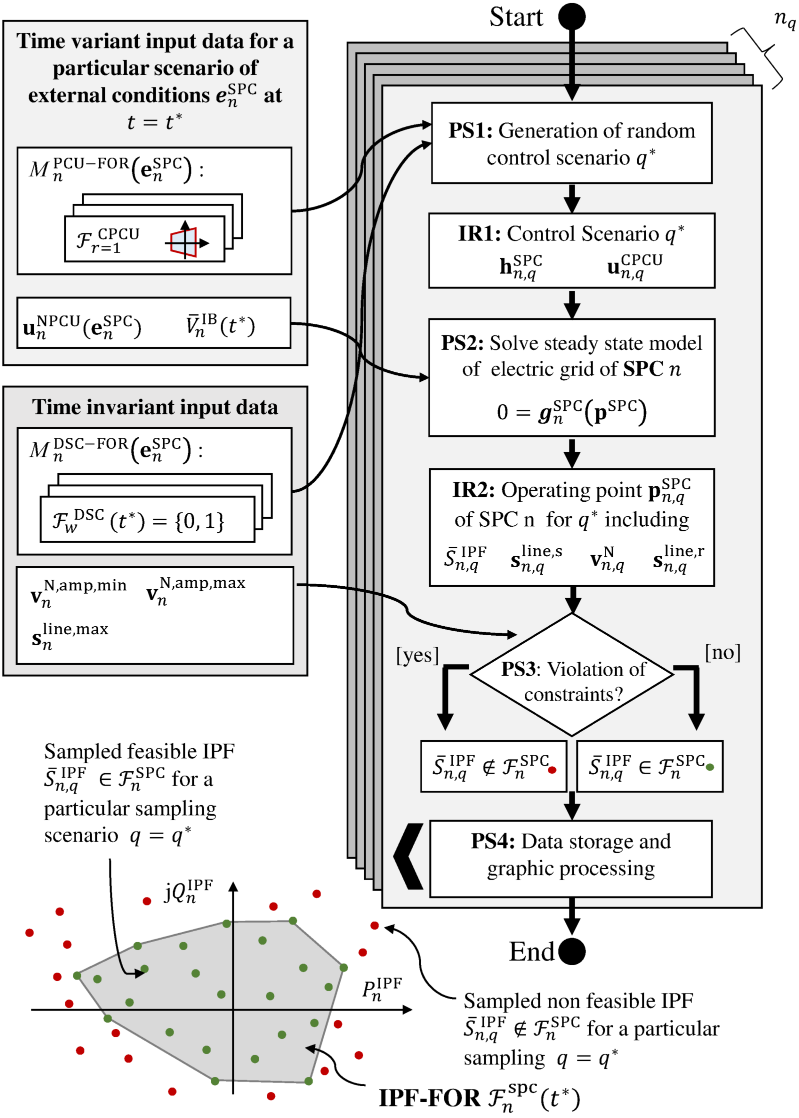


Figure 5.15: Method 1: Approximation of the IPF-FOR $\mathcal{F}_n^{SPC}$ under perfect knowledge of all influencing factors for a particular point in time $t = t^*$

is time-variant because it depends on the behaviour of both, the SPC connected to it and the state of the transmission network.

On the other hand, time-invariant input data are data which do not depend on a particular scenario of external factors and therefore remain constant over time, even if $\mathbf{e}_n^{\mathrm{SPC}}$ changes. Inputs that are considered to be time-invariant are the set $\mathcal{M}_n^{\mathrm{DSC-FOR}}$ which describes the range of possible switching combinations of discrete switching devices and the operational limits $\mathbf{v}^{\mathrm{N,amp,min}}$, $\mathbf{v}^{\mathrm{N,amp,max}}$, $\mathbf{s}^{\mathrm{line,max}}$ which restrict the operation of the electric grid.

This differentiation between time-variant and time-invariant inputs is in particular relevant for the computation of the evolution of the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ over time in section 5.7 and the probabilistic estimation of the IPF-FOR of a future time interval under consideration of forecasts of external influencing factors which is described in section 5.8.

Once the input data for a particular scenario of external influencing factors associated to a particular point in time $t = t^*$ is provided, the process required to determine the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ can start. The method is based on the random generation of n_q control scenarios $q \in Q$. Here, the index q denotes a randomly generated control scenario and n_q denotes the total number of randomly generated control scenarios. Each control scenario is defined by a particular value of the vector $\mathbf{h}_n^{\mathrm{SPC}}$ and a particular value of the vector $\mathbf{u}_n^{\mathrm{CPCU}}$ which together describe the behaviour of all the controllable components of the studied SPC.

As mentioned above, the process in question which is depicted in the right side of figure 5.15 is structured in four processing steps (PS1 - PS4) which are repeated n_q times. These processing steps are described in the following:

Processing step 1: Generation of a random control scenario q

In this processing step a control scenario q which is fully described by the vectors $\mathbf{u}_{n,q}^{\mathrm{CPCU}}$ and $\mathbf{h}_{n,q}^{\mathrm{SPC}}$ is randomly generated. To this, a random value is assigned to each element of these vectors under consideration of the FORs of the corresponding controllable PCUs and DSCs which are defined by the sets $\mathcal{M}_n^{\mathrm{PCU-FOR}}$ and $\mathcal{M}_n^{\mathrm{DSC-FOR}}$.

The intermediate result (IR1) of this processing step is

(i) a random value of $\mathbf{h}_{n,q}^{\mathrm{SPC}}$ for $q = q^*$ within the switching space of descrete switching components described by the set $\mathcal{M}_n^{\mathrm{DSC-FOR}}$ and

(ii) a random value of $\mathbf{u}_{n,q}^{\mathrm{CPCU}}$ for $q = q^*$ within the FORs of CPCUs described by $\mathcal{M}_n^{\mathrm{PCU-FOR}}$.

Processing step 2: Solve steady state model of electric grid of SPC n

The intermediate result (IR1) of the processing step 1 ($\mathbf{h}_{n,q}^{\mathrm{SPC}}$ and $\mathbf{u}_{n,q}^{\mathrm{CPCU}}$) is used in processing step 2 to compute the corresponding operation point $\mathbf{p}_{n,q}^{\mathrm{SPC}}$ of the electric grid of SPC n. To this, the model of the studied grid which is described by the system of equations

$$0 = g_n^{\mathrm{SPC}}(\mathbf{p}_{n,q}^{\mathrm{SPC}}) \tag{5.20}$$

and was introduced in section 5.1 is solved with a numeric solver (e.g. Newton Raphson method). To this, despite the random generated vectors $\mathbf{h}_{n,q}^{\mathrm{SPC}}$ and $\mathbf{u}_{n,q}^{\mathrm{CPCU}}$ the model requires the value of the interconnection bus voltage $\bar{V}_n^{\mathrm{IB}}(t^*)$ and the value of the vector $\mathbf{u}_n^{\mathrm{NPCU}}(t^*)$ (see Fig. 5.2).

The intermediate result IR2 of this processing step (see Fig. 5.15) is a randomly generated operating point $\mathbf{p}_{n,q}^{\mathrm{SPC}}$. Note here that this operating point is only one realization of all possible operating points which could be achieved by controlling the SPC by a suitable control. Note also that the operating point $\mathbf{p}_{n,q}^{\mathrm{SPC}}$ contains the subvectors $\bar{S}_{n,q}^{\mathrm{IPF}}$, $\mathbf{s}_{n,q}^{\mathrm{line,s}}$, $\mathbf{s}_{n,q}^{\mathrm{line,r}}$ and $\mathbf{v}_{n,q}^{\mathrm{N}}$. Here, $\bar{S}_{n,q}^{\mathrm{IPF}}$ is the IPF of SPC n which corresponds to the control scenario q, $\mathbf{s}_{n,q}^{\mathrm{line,s}}$ is a vector which maps the apparent power flows of the lines (sending end) of SPC n under the control scenario q, $\mathbf{s}_{n,q}^{\mathrm{line,r}}$ is a vector which maps the apparent power flows of the lines (receiving end) of SPC n under the control scenario q and $\mathbf{v}_{n,q}^{\mathrm{N}}$ is the vector which maps the voltages of the buses of the SPC n under the control scenario q.

Processing step 3: Classification of control scenarios and the corresponding operating points in feasible and non-feasible scenarios

Based on the intermediate result IR2, it can be verified if the value of $\mathbf{p}_{n,q}^{\mathrm{SPC}}$ which corresponds to the random generated control scenario $q = q^*$ violates any grid constraint (Equations 5.17, 5.18, and 5.19). In case grid constraints are violated, the randomly computed operation point $\mathbf{p}_{n,q}^{\mathrm{SPC}}$ is classified in this processing step as non-feasible. On the other hand, if all grid constraints are respected, the operation point $\mathbf{p}_{n,q}^{\mathrm{SPC}}$ is classified as feasible and thus an element of the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$.

The intermediate result IR3 of this processing step is a random generated operating point $\mathbf{p}_{n,q}^{\mathrm{SPC}}$ which has been classified as either a feasible or an unfeasible operation point.

Processing step 4: Data storage and graphic processing

In this processing step, the random generated and classified operating points associated with the single control scenarios $q \in Q$ are stored and a graphic representation of the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ is created.

As a result of the storing process, two sets of random sampled operating points are obtained. The set

$$\mathcal{M}_n^{\mathrm{FOP}} = \{\mathbf{p}_{n,q}^{\mathrm{SPC}} | \mathbf{p}_{n,q}^{\mathrm{SPC}} \ \forall \ q \text{ identified as feasible}\} \tag{5.21}$$

is the set of random generated operating points which would not lead to a violation of the grid constraints defined by the equations 5.17, 5.18 and 5.19. All these operating points could be achieved by the SPC control.

On the other hand, the set

$$\mathcal{M}_n^{\mathrm{NFOP}} = \{\mathbf{p}_{n,q}^{\mathrm{SPC}} | \mathbf{p}_{n,q}^{\mathrm{SPC}} \ \forall \ q \text{ identified as non feasible}\} \tag{5.22}$$

is the set of random generated operating points which would lead to a violation of the grid constraints defined by the equations 5.17, 5.18 and 5.19.

From $\mathcal{M}_n^{\mathrm{FOP}}$, an approximation of the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ can be obtained (see also definition 3) since the sampled operating points in $\mathcal{M}_n^{\mathrm{FOP}}$ contain the associated IPFs which in turn are elements of $\mathcal{F}_n^{\mathrm{SPC}}$.

To graphically illustrate the estimated IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ within this processing step, the feasible and unfeasible IPFs which were identified are plotted in the P-Q-plane. Feasible IPFs are plotted in green, and non-feasible IPFs are plotted in red. For $n_q \to \infty$ the resulting cloud of feasible (green) IPFs would represent the IPF-FOR of the studied SPC. However, choosing n_q pragmatically to make the computation feasible can also produce a good approximation. Finally, the IPF-FOR is approximated by a polygon which is described by the boundary points of the cloud of feasible IPFs which were numerically identified.

Output of the developed method for the description of the flexibility of an SPC to support the operation of the transmission network

By means of the method presented in this section, the random generated sets $\mathcal{M}_n^{\mathrm{FOP}}$ and $\mathcal{M}_n^{\mathrm{NFOP}}$ are obtained. Further, a graphical representation of the IPF-FOR of the studied SPC is generated and a vector containing the boundary points of $\mathcal{M}_n^{\mathrm{FOP}}$ is provided.

The generated data describes the flexibility of an SPC to support the operation of the transmission network by changes on its IPF. This information could be used in a future power system organized according to the SPC concept to provide information that the TSO could use for day-ahead and intra-day planning purposes and in this way coordinate the behaviour of the SPCs connected to its responsibility area. A concept for the cross voltage level coordination of a future power system organized according to the SPC concept has been described in section 3.9.

5.7 Time-variant behaviour of the IPF-FOR of a Smart Power Cell during a time interval

In the previous section, an approach for estimating the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}(t)$ of an SPC for a particular scenario of external influencing factors $\mathbf{e}_n^{\mathrm{SPC}}(t)$ at a particular point in time $t = t^*$ has been presented. Further, it has been stated that the vector $\mathbf{e}_n^{\mathrm{SPC}}(t)$ is time-variant and thus, also $\mathcal{F}_n^{\mathrm{SPC}}(t)$ can be expected to vary over time. This section explains how the evolution of the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}(t)$ during a time interval $t^0 \leq t \leq t^{\mathrm{end}}$ can be estimated.

To this aim, the method described in the previous section is repeated for different time steps $t = [t_1, t_2, ..., t_{n_s}]$. For each time step, the corresponding vector of external influencing factors $\mathbf{e}_n^{\mathrm{SPC}}(t)$ is considered and the IPF-FOR is computed. As a result of this process, we obtain a set of estimated IPF-FORs

$$\{\mathcal{F}_n^{\mathrm{SPC}}(t_1), \mathcal{F}_n^{\mathrm{SPC}}(t_2), ..., \mathcal{F}_n^{\mathrm{SPC}}(t_{n_s})\} \tag{5.23}$$

which represents the trajectory (the variation of position, quality and covered area) of the FOR of the studied SPC. The resulting trajectory can be illustrated in a three-dimensional space (P-Q-t) showing the evolution of the shape over time as figure 5.16 shows.

Exemplary reasons for the variability of the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ of an SPC over time are listed in the following:

(i) The FORs of wind energy converters depend on the current wind speed,

(ii) the FORs of flexible loads depend on the current social behaviour of customers,

(iii) the FORs of storages depend on their storage state and the social behaviour of customers,

(iv) the FORs of photovoltaic units depend on the current solar radiation and temperature,

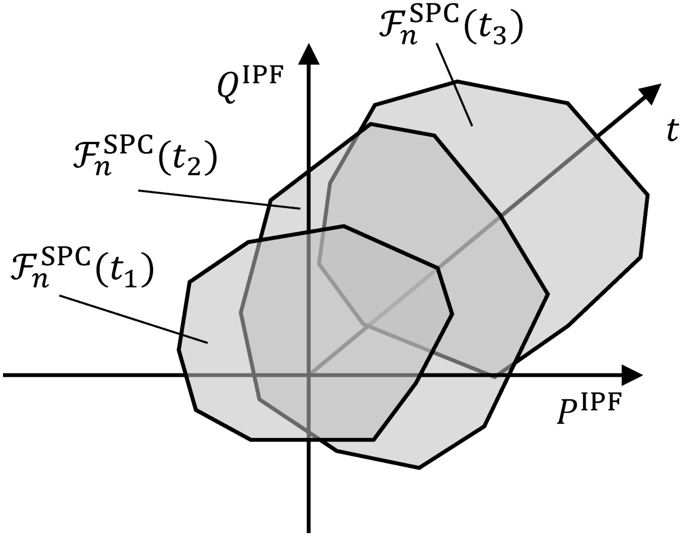


Figure 5.16: Evolution of the IPF-FOR $\mathcal{F}_n^{\text{SPC}}$(t) over time (snapshots)

(v) the active and reactive power behaviour of non-controllable PCUs depends on the voltage amplitude of their connection points which depend on the interconnection voltage of the SPC which can also be considered to be time-variant.

Determining the trajectory of the FOR of an SPC when the required models and input data is available can be seen as a straight forward task. However, in order to use the FOR for day-ahead and intra-day operational planning purposes, the FOR needs to be estimated in advance when the exact values of the input vectors required for its computation are not known yet. In the next section, a probabilistic method to estimate in advance the flexibility of an SPC to support the operation of the transmission network is described.

5.8 Probabilistic assessment of the flexibility of a Smart Power Cell to support the operation of the transmission grid (Method 2)

In the previous sections, an approach has been described that can be used to determine the flexibility of an SPC to support the operation of the transmission network by changes on its IPF. This is done by describing the flexibility which is available at a particular point in time $t = t^*$ by a shape in the complex P-Q-plane called IPF-FOR and denoted by $\mathcal{F}_n^{\mathrm{SPC}}(t)$. The developed approach assumes that all relevant time-variant influencing factors[7] which have an impact on the flexibility of an SPC are known. This means that to compute $\mathcal{F}_n^{\mathrm{SPC}}(t)$ at $t = t^*$, the value of the external influencing factors mapped by the vector $\mathbf{e}_n^{\mathrm{SPC}}(t^*)$ needs to be given.

The main benefit of describing the flexibility of an SPC, however, emerges when this information is available in advance, such that flexibility potentials which will be available in future time intervals can be considered in the context of day-ahead and intra-day operational planning. For this purpose, the flexibility of an SPC to adjust its IPF in future time intervals needs to be predicted beforehand. To make this possible, forecasts of external influencing factors $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}$ which are subject to uncertainty need to be considered. In this context the following question arises:

> How can the flexibility which an SPC will have in a future time interval to adjust its IPF can be described and predicted based on forecasts of external influencing factors which are subject to uncertainty?

As a contribution to finding a solution to this problem, in this section, a probabilistic approach is presented which can be applied to characterize the IPF-FOR of an SPC for a future time interval $\bar{i}$, for which only uncertain forecasts of time-variant influencing factors are available.

In the following section 5.8.1, first, relevant terminology for the description of the developed method is provided and basic concepts regarding the probabilistic description of random processes are introduced. Then, in section 5.8.2, the probabilistic description of influencing factors is addressed. Finally, the developed method is described in section 5.8.3.

5.8.1 Terminology and basic concepts required for the probabilistic method to estimate the future flexibility of Smart Power Cells

The developed approach to probabilistically describe the flexibility of an SPC which is presented in section 5.8.3 is founded on the probabilistic description of the future behaviour of the external influencing factors which are mapped by the vector $\mathbf{e}_n^{\mathrm{SPC}}(t)$. In the following relevant concepts and terms used for the

---

[7] E.g., wind speed, solar radiation, social behaviour.

probabilistic description of the future behaviour of external influencing factors are briefly introduced.

Random Variable

It is well known [2, 40], that the outcome of a random phenomenon - such as the instantaneous solar radiation measured by a Pyranometer installed at a particular geographical location - can be described by a continuous random variable X and its associated probability density function $f^X(x)$. Formally, a random variable is defined as a function $X : \Omega \rightarrow \mathbb{R}$ from the set of possible outcomes Ω to a measurable space $\mathbb{R}$.

The probability that a continuous random variable X takes on a value $a \leq X \leq b$ when its corresponding probability density function $f^X(x)$ is defined can be described by

$$Pr[a \leq X \leq b] = \int_a^b f^X(x)\ dx. \tag{5.24}$$

Random Processes

Consider a time-variant quantity - e.g. measured wind speed or solar radiation at a particular location - which is described by $x(t)$. The trajectory $x(t)$ for $t \leq 0$ (past) can be obtained by accumulating observations or measurements during a period of time situated in the past and can be described by the time series $\{x(t), t = [t_1, t_2, ..., t_n]\}$.

The trajectory $x(t)$ for a future time interval $t \in [0, \infty)$, however, is not known and can only be described probabilistically, e.g, by a random process $\{X(t), t \in [0, \infty)\}$ which is a mathematical object composed of an infinite indexed collection of random variables $X(t)$ for $t \in [0, \infty)$ and describes a random phenomenon which evolves over time. The possible realizations or outcomes of a random process $\{X(t), t \in [0, \infty)\}$ are sample trajectories of x(t) for $t > 0$. This is suggested in Fig. 5.17 where three exemplary realizations $\hat{x}_1(t)$, $\hat{x}_2(t)$ and $\hat{x}_3(t)$ of an exemplary random process $X(t), t \in [0, \infty)$ are illustrated by dashed lines. Notice that each trajectory $\hat{x}_w(t), t \in [0, \infty)$ is one possible outcome of the set of all possible outcomes ω of $X(t)$.

When a period of time is considered on the retrospective, the actual trajectory

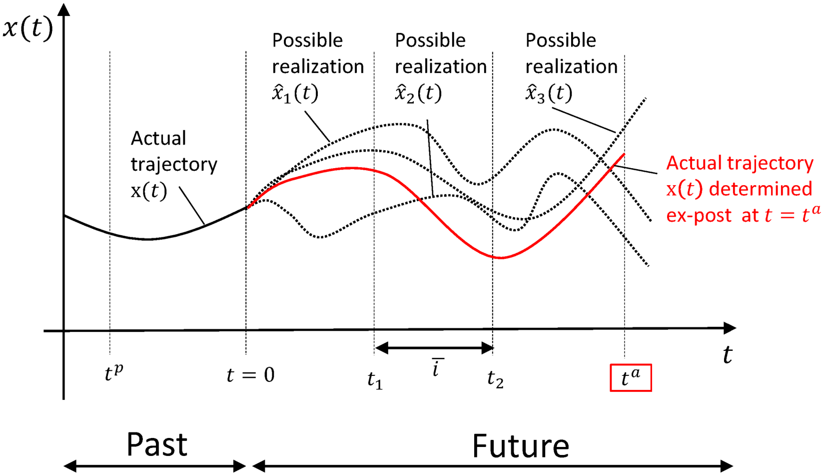


Figure 5.17: Overview of concepts related to the description of time-variant quantities as random processes

of $x(t)$ can be assumed to be known. This is suggested by figure 5.17 which also depicts the actual trajectory of the time-variant quantity x(t) for $t > 0$ in red. Notice, however, that at $t = 0$ this trajectory is unknown. x(t) for $0 \leq t \leq t^a$ can only be obtained in the retrospective, that is at $t \geq t^a$.

A comprehensive overview of the topic "Random Processes" can be found e.g. in [2, 40].

Forecasts of time-variant quantities

When measured time series of time-variant quantities observed in nature are analysed, very often it can be found out that these quantities follow more or less some regular pattern in the long term. This fact can be used to develop a mathematical model which captures the stochastic characteristics of the underlying processes which determine the stochastic behaviour of the observed quantity. Based on such a model, a forecasting method can be developed which can be used to predict the future behaviour of a time-variant quantity. An overview of time series forecasting methods can be found in [2].

Specifically, this means that, if a particular future time interval $\bar{i} = [t_1, t_2]$ is considered, a forecasting method can be used to find an estimation $\tilde{x}(\bar{i})$ for that

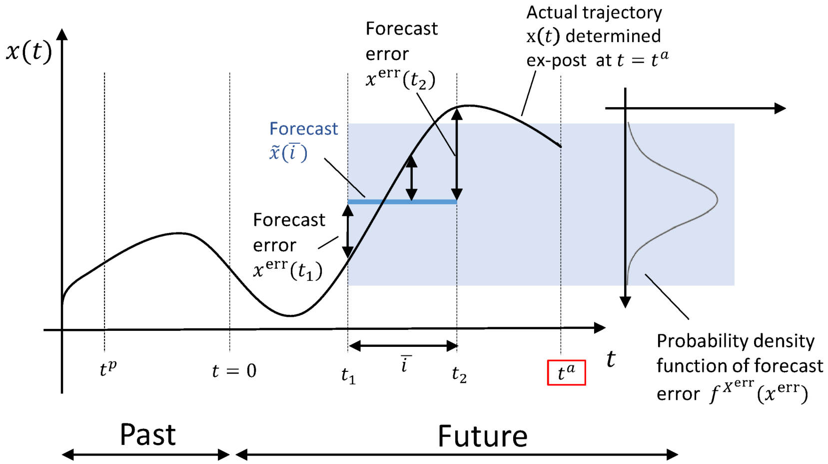


Figure 5.18: Overview of concepts related to the uncertainty associated to forecasts of time-variant quantities

particular interval. We call this estimation a forecast $\tilde{x}(\bar{i})$ for the time interval $\bar{i}$. This is suggested in figure 5.18, where a forecast $\tilde{x}(\bar{i})$ performed at $t = t^p$ for the future time interval $\bar{i}$ is illustrated by the blue line.

A forecast is by definition always subject to a forecast error $x^{\text{err}}(t)$ which is defined as

$$x^{\text{err}}(t) = \tilde{x}(\bar{i}) - x(t). \tag{5.25}$$

This is also suggested in figure 5.18, where some exemplary forecast errors signalized by black arrows are depicted.

By definition, a forecast error can only be determined ex-post, that is, when the actual trajectory $\{x(t), t \in \bar{i}\}$ is known. However, when a forecast $\tilde{x}(\bar{i})$ for a particular future time interval $\bar{i}$ has been found, the associated forecast error x^{err} can be probabilistically described by the random variable X^{err} and the corresponding probability density function $f^{X^{\text{err}}}(x^{\text{err}})$. This is also suggested by figure 5.18. The probability density function $f^{X^{\text{err}}}(x^{\text{err}})$ describes the likelihood that at a specific moment $t \in \bar{i}$ the random variable X^{err} takes a value $x^{\text{err,ll}} \leq x^{\text{err}}(t) \leq x^{\text{err,ul}}$.

Matrix notation

The terms and concepts addressed above are also valid for sets of random processes which can be compactly described using matrix notation. To this, a set of n random variables $X_1, X_2, ..., X_n$ can be described by an n-dimensional random vector $\mathbf{X}(t)$ whose stochastic behaviour is defined by a corresponding set of probability density functions $\mathcal{D}^{\mathbf{X}}$ which contains the probability density functions $f^{X_1}(x_1), f^{X_2}(x_2), ..., f^{X_n}(x_n)$ of the single random variables $X_1, X_2, ..., X_n$. Note that other objects such as random processes, forecasts and forecast errors can be written using matrix notation in an analogical way.

5.8.2 Treatment of external influencing factors as random processes

As previously suggested, the external influencing factors which influence the flexibility of an SPC such as the wind speed, the solar radiation or the social behaviour of network users can be mapped by the vector $\mathbf{e}_n^{\mathrm{SPC}}(t)$. Assuming that $t = 0$ refers to current time, for $t \leq 0$, the trajectory of $\mathbf{e}_n^{\mathrm{SPC}}(t)$ can be obtained by the accumulation of observations or measurements over a period of time. Thus, describing the trajectory of the vector $\mathbf{e}_n^{\mathrm{SPC}}(t)$ in the retrospective ($t \leq 0$) can be considered to be a straightforward task.

When the trajectories of external influencing factors, however, need to be predicted for a time interval $\bar{i}$ which is situated in the future, a probabilistic description is required. This is due to the fact that for $t \in [0, \infty)$, each of the influencing factors which are mapped by the vector $\mathbf{e}_n^{\mathrm{SPC}}(t)$ can be considered to be a random process. This means that at $t = 0$ the values which $\mathbf{e}_n^{\mathrm{SPC}}(t)$ will actually take for $t \geq 0$ are unknown and can only be described probabilistically.

To this, the future time line for $t \geq 0$ can be considered to be divided in a set of time intervals $\bar{i}_1, \bar{i}_2, ...$ For each time interval $\bar{i}$ a forecast of external influencing factors $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$ can be determined. The uncertainty associated to each forecast $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$ can be described by the random variable $\mathbf{E}_n^{\mathrm{SPC,err}}(t)$ and the corresponding set of probability density functions $\mathcal{D}_n^{\mathrm{SPC,err}}(t)$. The random variable $\mathbf{E}_n^{\mathrm{SPC,err}}(t)$ describes probabilistically the range and probability of forecasting errors that may occur in a future time interval $\bar{i}$, when a prediction $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$ is given and its uncertainty is described by the set of probability density functions $\mathcal{D}_n^{\mathrm{SPC,err}}$.

Based on the forecast of external influencing factors $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$ and the associated random variable $\mathbf{E}_n^{\mathrm{SPC,err}}(t)$ which describes its uncertainty, the random vector

$$\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i}) = \tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i}) + \mathbf{E}_n^{\mathrm{SPC,err}}(\bar{i}) \tag{5.26}$$

can be determined for each future time interval $\bar{i}_1, \bar{i}_2, \ldots$.

The random vector $\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i})$ describes probabilistically the external influencing factors expected in the future time interval $(\bar{i})$. Note that $\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i})$ is also a probabilistic quantity whose outcome depends on a random phenomenon which can be described by the set of probability density functions $\mathcal{D}_n^{\mathrm{SPC,dist}}$.

5.8.3 Developed method for the probabilistic assessment of the flexibility of a Smart Power Cell

In this section the method which was developed to estimate the flexibility that an SPC will have in a future time interval $\bar{i}$ is described. The developed method is structured in 5 processing steps and is illustrated in Fig. 5.19.

The method requires as an input a forecast of external influencing factors $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$ for $\bar{i}$ and a probabilistic forecast error scenario $\mathbf{E}_n^{\mathrm{SPC,err}}$ together with the corresponding set of probability density functions $\mathcal{D}_n^{\mathrm{SPC,err}}$.

Processing step 1: Obtain probabilistic scenario of influencing factors

In this processing step a probabilistic scenario of influencing factors $\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i})$ for the time interval $\bar{i}$ is determined. This scenario $\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i})$ is obtained - with equation 5.26 - from the forecast of influencing factors $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$, the probabilistic scenario of forecast errors $\mathbf{E}_n^{\mathrm{SPC,err}}(\bar{i})$ and the corresponding set of probability density functions $\mathcal{D}_n^{\mathrm{SPC,err}}$. The intermediate result IR1 of this processing step is the random variable $\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i})$ and the corresponding set of probability density functions $\mathcal{D}_n^{\mathrm{SPC,dist}}(\bar{i})$.

Processing step 2: Generate random realization of random variable $\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i})$

In this processing step, a realization $\hat{\mathbf{e}}_{n,j}^{\mathrm{SPC}}(\bar{i})$ of the random variable $\mathbf{E}_n^{\mathrm{SPC,dist}}(\bar{i})$ is randomly generated. Notice that this processing step is repeated n_j times as figure 5.19 indicates. The intermediate result IR2 of this processing step is the random realization $\hat{\mathbf{e}}_{n,j}^{\mathrm{SPC}}(\bar{i})$ for the current iteration j.

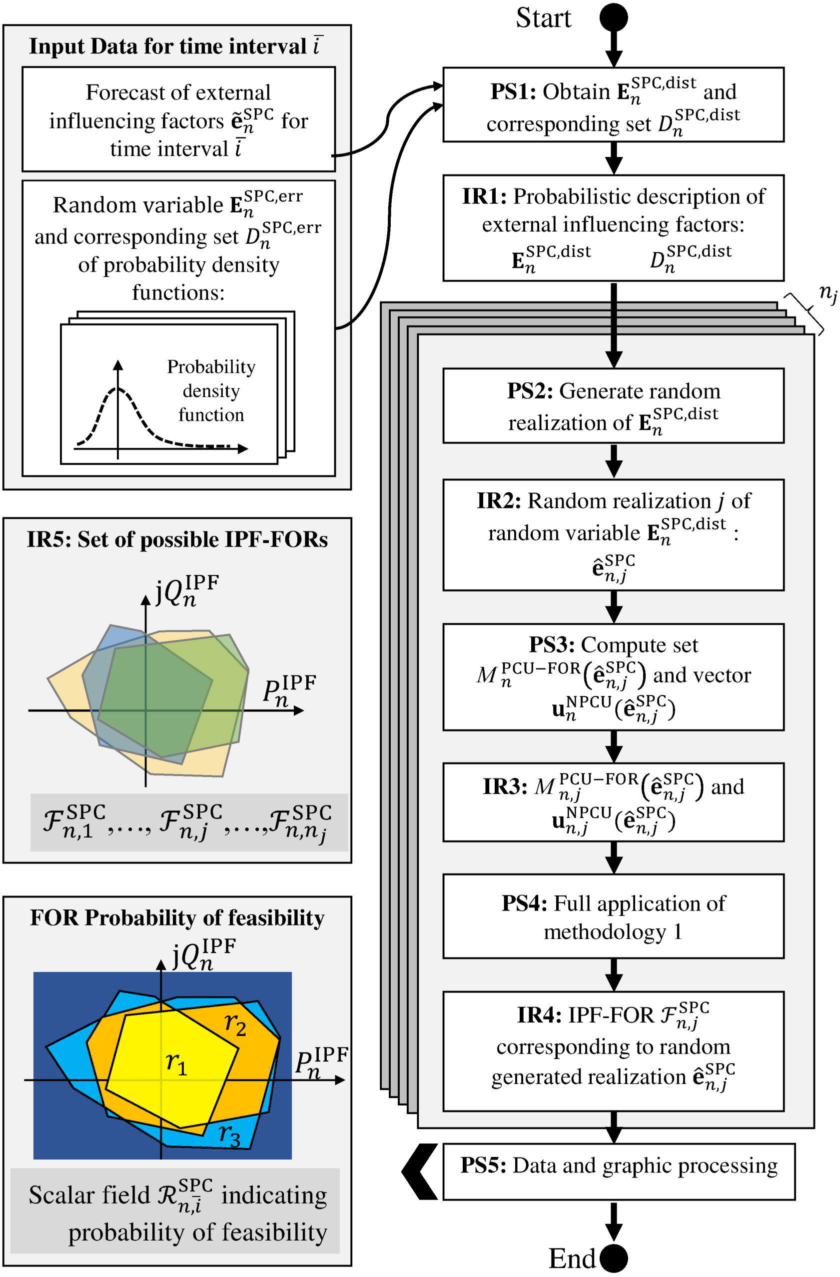


Figure 5.19: Method 2: Probabilistic assessment of flexibility of an SPC to adjust its IPF to support the operation of the transmission system

Processing step 3: Compute set of FORs of controllable PCUs and apparent behaviour vector of non-controllable PCUs

In this processing step, the set of FORs of controllable PCUs $\mathcal{M}_n^{\mathrm{PCU-FOR}}(\hat{\mathbf{e}}_n^{\mathrm{SPC}})$ and the apparent power behaviour vector of non-controllable PCUs $\mathbf{u}_n^{\mathrm{NPCU}}(\hat{\mathbf{e}}_n^{\mathrm{SPC}})$ associated with the realization $\hat{\mathbf{e}}_{n,j}^{\mathrm{SPC}}(\bar{i})$ is obtained. Notice that the dependency of the set $\mathcal{M}_n^{\mathrm{PCU-FOR}}$ and $\mathbf{u}_n^{\mathrm{NPCU}}$ on the vector $\mathbf{e}_{n,j}^{\mathrm{SPC}}(\bar{i})$ has already been described in section 5.1.

The intermediate result IR3 is the set $\mathcal{M}_{n,j}^{\mathrm{PCU-FOR}}$ and the vector $\mathbf{u}_{n,j}^{\mathrm{NPCU}}$ associated with the current iteration j. This intermediate result is used in the next processing step to compute the IPF-FOR which would result for the randomly generated scenario of external influencing factors $\hat{\mathbf{e}}_{n,j}^{\mathrm{SPC}}(\bar{i})$.

Processing step 4: Compute the IPF-FOR associated with the current iteration j and the corresponding scenario of external influencing factors $\hat{\mathbf{e}}_{n,j}^{\mathrm{SPC}}(\bar{i})$

In this processing step, the IPF-FOR $\mathcal{F}_{n,j}^{\mathrm{SPC}}$ for the current iteration j and the corresponding scenario of external influencing factors $\hat{\mathbf{e}}_{n,j}^{\mathrm{SPC}}(\bar{i})$ is computed. To this, method 1 described in section 5.6 is fully applied. The intermediate result is a possible realization $\mathcal{F}_{n,j}^{\mathrm{SPC}}$ which is a single sample of the population of possible IPF-FOR outcomes which could take place according to the considered forecast of external influencing factors $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$ and the probabilistic scenario of forecast errors $\mathbf{E}_n^{\mathrm{SPC,err}}$.

Processing step 5: Data and graphic processing

In this processing step, the intermediate results of each iteration $j \in \{1, 2, ..., n_j\}$ are stored and processed.

The intermediate result IR5 of this processing step is a set of n_j randomly generated IPF-FORs $\{\mathcal{F}_{n,1}^{\mathrm{SPC}}, ..., \mathcal{F}_{n,j}^{\mathrm{SPC}}, ..., \mathcal{F}_{n,n_j}^{\mathrm{SPC}}\}$. Each randomly generated IPF-FOR $\mathcal{F}_{n,j}^{\mathrm{SPC}}$ corresponds to a randomly generated possible scenario of external influencing factors $\hat{\mathbf{e}}_n^{\mathrm{SPC}}, j(\bar{i})$. This set can be thought of as a sample of the population of possible IPF-FORs outcomes which are stochastically determined by the considered forecast of external influencing factors $\tilde{\mathbf{e}}_n^{\mathrm{SPC}}(\bar{i})$ and the probabilistic scenario of forecast errors $\mathbf{E}_n^{\mathrm{SPC,dist}}$.

Output of the developed method for the probabilistic estimation of the flexibility of an SPC to support the operation of the transmission network

The final result of method 2 is a probabilistic description of the flexibility of the studied SPC for the time interval $\bar{i}$. This result is obtained by introducing the metric r which describes the probability of feasibility of a particular IPF $\bar{S}_n^{\mathrm{IPF}}$ in a future time interval $\bar{i}$. By associating a value of r to each possible IPF, the scalar field $\mathcal{R}_{n,\bar{i}}^{\mathrm{SPC}}$ can be determined. The scalar field $\mathcal{R}_{n,\bar{i}}^{\mathrm{SPC}}$ associates a probability r to each point in the P-Q-plane and probabilistically describes which IPFs are likely to be feasible. To obtain the field $\mathcal{R}_{n,\bar{i}}^{\mathrm{SPC}}$, the sampled IPF-FORs $\{\mathcal{F}_{n,1}^{\mathrm{SPC}}, ..., \mathcal{F}_{n,j}^{\mathrm{SPC}}, ..., \mathcal{F}_{n,n_j}^{\mathrm{SPC}}\}$ which were randomly generated within processing step 5 are used to assign to a sample of points in the P-Q-plane a relative frequency which indicates how often these points were part of the randomly generated IPF-FORs. By this, points within the P-Q-plane can be identified that are elements of all randomly generated IPF-FORs. These points are assumed to have a probability of feasibility $r = 100\%$. On the other hand, points within the P-Q-plane can be identified that are not an element of any randomly generated IPF-FOR. These points are assumed to have a probability of feasibility of $r = 0\%$. All remaining points within the P-Q-plane are elements of a fraction of the sampled IPF-FORs. Depending on their relative frequency the probability of these points are assumed to be $0 < r < 100$. In section 5.9.4, the results of a case study which was conducted to demonstrate the developed method are presented. Fig. 5.23 shows two exemplary scalar fields $\mathcal{R}_{n,\bar{i}}^{\mathrm{SPC}}$ which were determined by an implementation of the method described in this section.

5.9 Case studies and simulation results

In order to test and demonstrate the methods described in this chapter (see sections 5.6, 5.7 and 5.8.3) several case studies using different test systems were conducted and described in previous work and in the context of master theses, e.g. in [ST2, ST4, DM10, DM11].

In this section, selected results of case studies which were conducted to demonstrate the developed methods are presented. To this, first, in section 5.9.1 a distribution test system used to model an exemplary SPC is described. Then, in section 5.9.2, 5.9.3 and 5.9.4 exemplary results which where harvested by implementations of the methods developed in this chapter are presented.

5.9.1 Distribution network test system developed to model Smart Power Cells

In order to test the methods described in this chapter, a distribution test system which builds upon the European configuration of the medium voltage distribution network benchmark described in [13] was developed and implemented. The fundamental structure of the test system is depicted in Fig. 5.20. As illustrated, the test system is composed of two feeders: feeder 1 consists of 11 (20 kV) buses interconnected by 12 lines and cables. Feeder two consists of 3 buses interconnected by two lines. The system incorporates three circuit breakers. Depending on their switching state, the test grid can be operated in a radial or in a meshed way. Each feeder is connected to the transmission network via an OLTC transformer which can adopt 17 tap positions. These OLTCs enable the exchange of active and reactive power between the transmission network and the feeders of the test system which are operated at medium voltage level. The developed test system includes several models of controllable and non-controllable PCUs.

To perform steady-state simulations (load flow studies), the distribution test system was implemented in Matlab using MATPOWER 6.0 [102]. To this, the test system data documented in [13] was used to create a MATPOWER case [102] which is a MATLAB function containing a set of data matrices which specify the input data required to run steady-state simulations. Based on this implementation, the state of the electric grid of the test system can be determined provided that enough data is given to solve the load-flow problem as has been discussed previously in section 4.1. A detailed documentation of the data required to perform load flow studies using MATPOWER can be found in [103].

Note that in this implementation, the transmission network is modelled as a Thévenin equivalent [98] connected to bus 0 of the test system (see Fig 5.20). Further, PCUs are modelled as active and reactive power sources and sinks located at the buses they are connected with. The active and reactive power behaviour of non-controllable power conversion units is modelled as a function of the external influencing factors vector $\mathbf{e}_n^{\mathrm{SPC}}$. The active and reactive power behaviour of controllable power conversion units is modelled as a function of the vector $\mathbf{u}_n^{\mathrm{CPCU}}$ and the set $\mathcal{M}_n^{\mathrm{PCU-FOR}}$ which contains the FORs of the PCUs which are connected to the studied network.

With this implementation, the steady-state of the test system can be determined for any vector $\mathbf{u}_n^{\mathrm{CPCU}}$ when the vector of external influencing factors $\mathbf{e}_n^{\mathrm{SPC}}$ is provided and the Thévenin voltage [98] of the Thévenin equivalent is given.

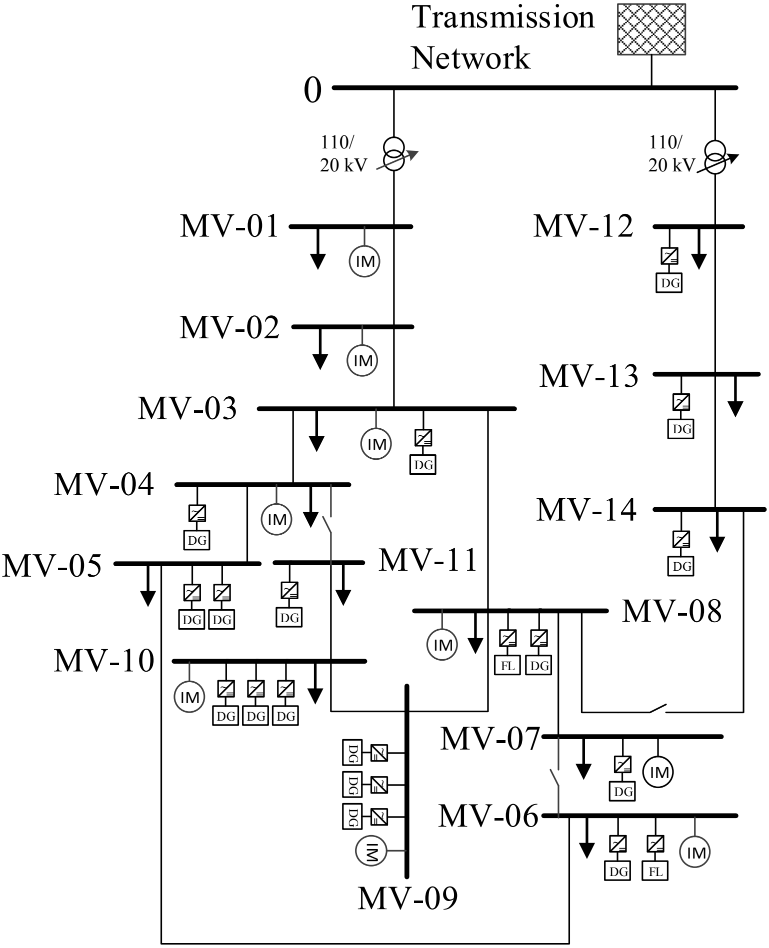


Figure 5.20: Distribution network configuration based on [13] used to model SPCs

5.9.2 Case Study I-a: Demonstration of the developed method to describe the flexibility of a Smart Power Cell to support the operation of the transmission network by adjusting its Interconnection Power Flow

In section 5.6, a method to approximate the IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ of a particular SPC n for a known scenario of external influencing factors $\mathbf{e}^{\mathrm{SPC}}(t)$ at a particular point in time $t = t^*$ is described. In this section, exemplary results of an implementation of the developed method are presented. To test the method, the distribution test system described in the previous section was used. The method was implemented in Matlab using MATPOWER 6.0 [102]. The thermal limits of the medium voltage test grid were defined as proposed in [17]. The voltage magnitude limits are assumed to be $\mathrm{V}_i^{\mathrm{N,amp,min}} = 0.9$ p.u and $\mathrm{V}_i^{\mathrm{N,amp,max}} = 1.1$ p.u for all buses i of the SPC n.

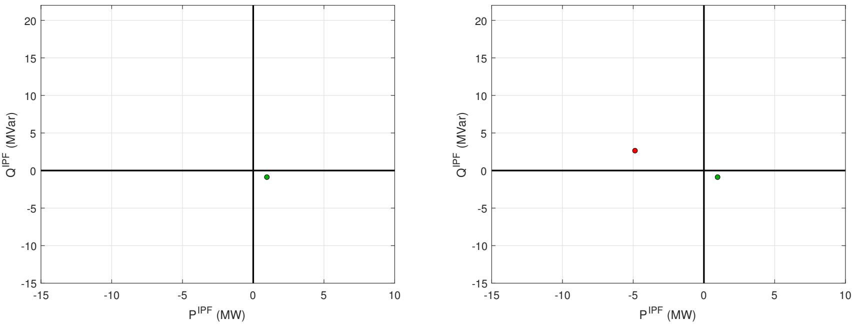
Selected results of the conducted case study are depicted in figure 5.21. All sub-figures correspond to the same scenario of external influencing factors $\mathbf{e}_n^{\mathrm{SPC}}(t^*)$. The sub-figure 5.21-f shows the approximated IPF-FOR $\mathcal{F}_n^{\mathrm{SPC}}$ of the test system which was obtained applying method 1 for the particular scenario of external influencing factors $\mathbf{e}^{\mathrm{SPC}}(t^*)$. To determine the IPF-FOR $\mathcal{F}^{\mathrm{SPC}}(t^*)$, a sample size of $n_q = 9 \cdot 10^4$ randomly generated control scenarios q was chosen (see Fig. 5.15). The resulting IPF-FOR describes[8] the flexibility of the test SPC to control its IPF at the observed point in time t^*.

In order to trace how the IPF-FOR depicted in figure 5.21-f was generated, intermediate results are shown in the figures 5.21-a to 5.21-e. In Figure 5.21-a one random generated IPF that was obtained after the first iteration of method 1 (see Fig. 5.15) is plotted. The plotted IPF is green because it was categorized as feasible in the processing step 3 of the iteration $q = 1$, i.e. the corresponding operating point does not violate any operational constraints.

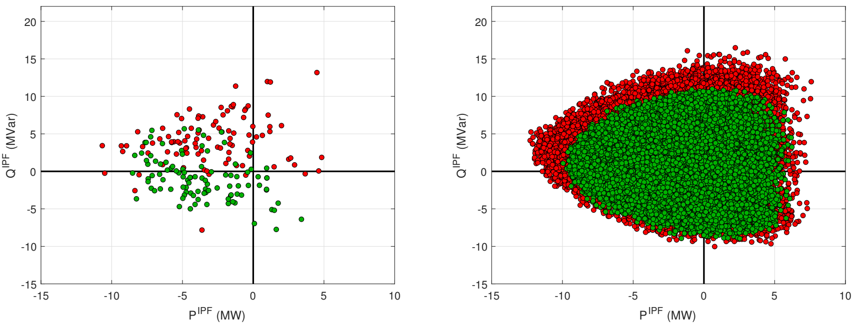
In Fig. 5.21-b, the IPF obtained after the iteration $q = 2$ has additionally been plotted. This IPF is red because it corresponds to an operating point which violates at least one operational constraint. A sample of randomly generated IPFs which was obtained after 100 iterations ($n_q = 100$) is depicted in Fig. 5.21-c. The figure already gives some insight regarding the form and position of the IPF-FOR, however, it is evident that the sample size is not sufficient to

---

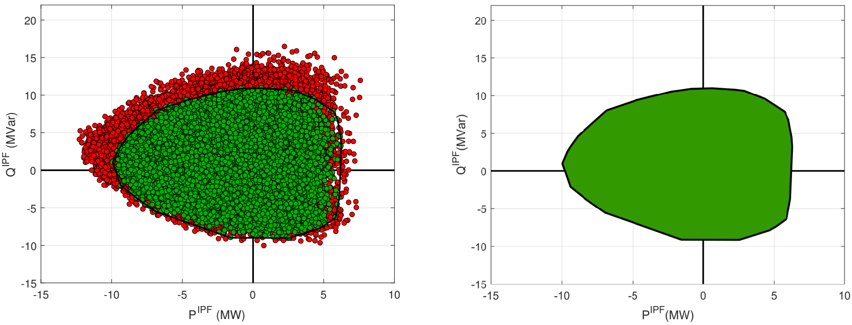
[8] The green area describes the set of feasible IPFs which the monitoring and control system of the studied SPC can achieve by controlling the controllable PCUs of the test system without violating operational constraints. This means that if a TSO requests an IPF setpoint within the IPF-FOR, the control system of the SPC would be able to meet this request without causing a violation of any operational limit.



(a) Sampled IPFs for $n_q = 1$ (b) Sampled IPFs for $n_q = 2$



(c) Sampled IPFs for $n_q = 100$ (d) Sampled IPFs for $n_q = 9 \cdot 10^4$



(e) Convex hull over boundary points of sampled IPFs (f) Approximated IPF-FOR

Figure 5.21: Case study I-a: Intermediate and final results obtained with the developed method for flexibility estimation of an SPC (method 1)

provide a conclusive description.

Figure 5.21-d shows the sample of randomly generated IPFs after $n_q = 9 * 10^4$. Here, the IPF-FOR of the test system for the studied scenario can be clearly recognized. Finally, the polygon which is created connecting the boundary points of the generated set of feasible IPFs is illustrated in Fig. 5.21-e. By this polygon, a sparse description of the determined set can be provided. The area within the polygon represents the approximated IPF-FOR which leads to the final result plotted in Fig. 5.21-f.

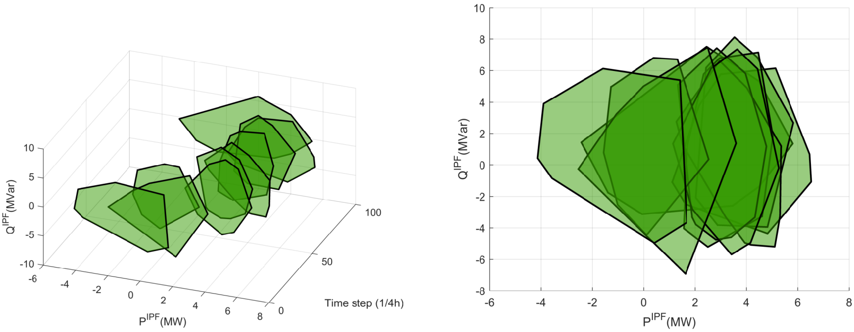
5.9.3 Case Study I-b: Evolution of the IPF-FOR (flexibility) of a Smart Power Cell over time

As discussed in section 5.7, the IPF-FOR of an SPC is a time-variant property. This is due to the fact that the IPF-FOR of an SPC depends on external influencing factors - such as the wind velocity, the temperature or the solar radiation - which are quantities which also vary over time. To demonstrate that this statement is true, the IPF-FORs of the test system described in section 5.9.1 was determined with method 1 for a time series of external influencing factors. The results of the case study are illustrated in figure 5.22. As expected, the figures clearly show that the form, area, and position of the IPF-FOR change for each considered scenario of external influencing factors.

These results make evident that the flexibility of an SPC to support the operation of the transmission network is not constant and varies over time. Thus, when the contribution of SPCs to the operation of the system is planned in the context of day-ahead and intra-day operational planning, it es necessary to estimate the flexibility of each SPC for particular future time intervals.

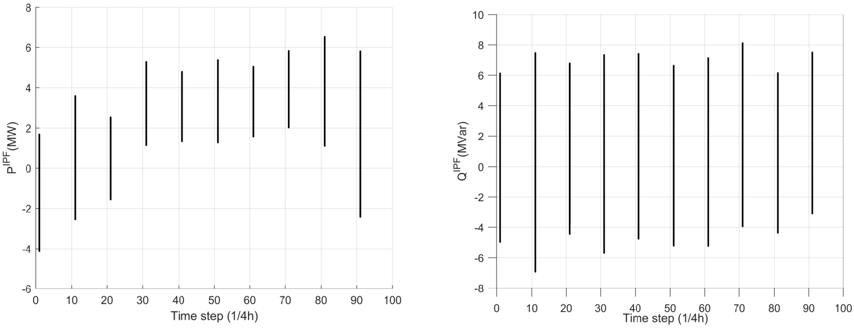
5.9.4 Case Study I-c: Probability of Feasibility

In section 5.8, a probabilistic approach to characterize the IPF-FOR of an SPC for a future time interval $\bar{i}$ under consideration of forecasts of time-variant influencing factors which are subject to uncertainty was described. In this section, exemplary results of an implementation of the developed method are presented. To test the method, the distribution test system described in section 5.9.1 was used. Further, the method 2 described in section 5.8 was implemented in Matlab using MATPOWER 6.0 [102]. The thermal limits of the medium voltage test grid were defined as proposed in [17]. The voltage magnitude limits are assumed to be $\mathrm{V}_i^{\mathrm{N,amp,min}} = 0.9$ p.u and $\mathrm{V}_i^{\mathrm{N,amp,max}} = 1.1$ p.u for all buses i of the SPC



(a) Evolution of the IPF-FOR of the test system over time - perspective 1

(b) Evolution of the IPF-FOR of the test system over time - perspective 2



(c) Evolution of the IPF-FOR of the test system over time - perspective 3

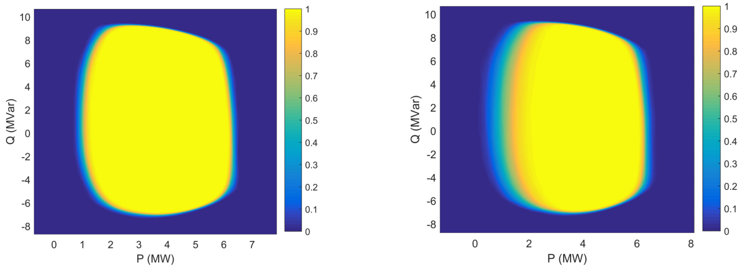
(d) Evolution of the IPF-FOR of the test system over time - perspective 4

Figure 5.22: Case Study I-b: Evolution of the IPF-FOR of the test system over time

n.

Selected results of the conducted case study are illustrated in figure 5.23. Both figures show the scalar field $\mathcal{R}^{\mathrm{SPC}}_{n,\bar{i}}$ which was obtained for a particular future time interval $\bar{i}$ and the corresponding scenario of external influencing factors $\tilde{\mathrm{e}}^{\mathrm{SPC}}_{n}$. However, two different sets of probability density functions of forecast errors $\mathcal{D}^{\mathrm{SPC,err}}_{n}$ (see figure 5.19) were considered.

The scalar fields $\mathcal{R}^{\mathrm{SPC}}_{n,\bar{i}}$ probabilistically describe the flexibility of an SPC to adapt its IPF in a future time interval $\bar{i}$ in case this is requested by the transmission system operator. To this, the $\mathcal{R}^{\mathrm{SPC}}_{n,\bar{i}}$ indicates the likelihood that a particular IPF can be achieved by controlling the components of the SPC based



(a) Scalar field $\mathcal{R}^{\mathrm{SPC}}_{n,\bar{i}}$ for uncertainty scenario A

(b) Scalar field $\mathcal{R}^{\mathrm{SPC}}_{n,\bar{i}}$ for uncertainty scenario B

Figure 5.23: Case I-c: Probabilistic description of the flexibility of an SPC to adapt its IPF to support the operation of the transmission network

on a forecast of influencing factors $\tilde{\mathbf{e}}^{\mathrm{SPC}}_{n}$ and the probabilistic description of the uncertainty associated with that particular forecast in form of a set of probability density functions of forecast errors $\mathcal{D}^{\mathrm{SPC,err}}_{n}$.

5.10 Summary

In a power system organized according to the SPC concept, SPCs will participate in the operation of the transmission system by adjusting their active and reactive IPFs on demand. Thus, operational interventions which today are provided by conventional power plants can be substituted. These interventions are required for example for congestion and voltage management or for increasing the system efficiency as has been discussed in chapter 2. In the previous sections, two methods for estimating the flexibility of an SPC to change its IPF have been presented. Method 1 can be used to estimate the flexibility of an SPC under the assumption that all external determinants are known. The result of this method is the IPF-FOR of the studied SPC for a particular point in time. The IPF-FOR describes the flexibility of an SPC to adjust its IPF without violating operational limits. Method 2, in the other hand, can be used to probabilistically estimate the flexibility that an SPC will have in a future time interval based on forecasts of external determinants. The result of this method is a scalar field which describes the likelihood the a particular IPF will be possible to be adjusted if it is requested by a superimposed monitoring and control system. In future, methods of this type could be used to provide information to the TSO regarding the operational flexibility available to operate the system. In this manner, the TSO could take operational decisions under consideration of the flexibility available in lower voltage levels and by this integrate PCUs connected at distribution networks in the operation of the entire system. To this, TSOs would determine IPF setpoints for the SPCs connected to their responsibility area which the SPCs would need to follow. This requires a control system implemented in each SPC such that IPFs can be controlled on demand to follow reference values. A control scheme to control the IPF of an SPC by controlling the behaviour of its PCUs is presented in the next section.

6 Control scheme for Interconnection Power Flow control of a Smart Power Cell

In chapter 3, a system architecture and operational concept for a future power system has been presented. The concept is founded on the idea of organizing the distribution network level of a future power system in grid subsections called SPCs which can be thought of as monitorable and controllable entities which inject (consume) active and reactive power into (from) particular buses of the transmission network. The behaviour of SPCs is supervised and controlled by a superimposed monitoring and control system which coordinates their behaviour in such a way that the entire system can be operated in a secure, stable and efficient way.

As discussed in section 3.4, the superimposed monitoring and control system can influence the behaviour of SPCs in several ways in order to support the operation of the transmission system. However, this chapter focuses on the IPF control and describes in this context a control scheme which was developed to control the active and reactive IPF of an SPC according to setpoints set by a superimposed monitoring and control system at the transmission level.

This chapter is structured as follows: First, in section 6.1, a brief survey on control schemes for coordinating the interactions of transmission and distribution networks is presented. Then, the scheme which was developed in previous work [DM9, DM12, DM14] is described in section 6.2, 6.3 and 6.5. Finally, selected results of case studies which were conducted to demonstrate and test the scheme are presented in section 6.6.

6.1 Brief survey on control schemes for coordinating the interactions of distribution networks with the transmission grid

The increasing interest in TSO-DSO coordination is reflected in many recent publications which suggest several methods and schemes to engage distribution networks in the provision of ancillary services at the transmission level. For example, in [5, 11, 75, 94, 100] the focus is set on exploring how distribution networks can participate in the regulation of transmission voltages by means of suitable control schemes. In [57, 104], the relaxation of congestions at transmission network level by the suitable control of distribution networks is discussed and approaches for that purpose are suggested. Furthermore, methods for the participation of distribution networks on the provision of balancing services and frequency control have been discussed e.g. in [38, 77].

Other contributions address the TSO-DSO coordination problem in a more general way, focussing on controlling the apparent power that distribution networks exchange with the transmission grid which in this thesis is called IPF (see also section 3.7). This is mainly motivated by two ideas: (i) the interaction of a distribution network with a transmission network at a given moment can be described by the corresponding IPF and (ii) the majority of services which a distribution network can provide to a transmission network can be induced by adjusting its IPF. Methods to control the reactive IPF have been proposed e.g. in [12, 50, 62, 68, 81, 84, 96]. On the other hand, methods and schemes to control the active IPF are suggested for instance in [9, 80, 83, 85, DM19]. Surprisingly, only few contributions [24, DM9, DM12, DM14, 86] focus on the simultaneous control of both, active and reactive IPF. This, however, is of paramount importance, since changes in the active and reactive power behaviour of a distribution network are highly interrelated and therefore, a simultaneous control is required [DM12]. In the next sections, a control scheme is presented that was developed to simultaneously control the active and reactive IPF of an SPC. In particular, the control scheme is able to induce changes in the IPF without causing violations of operational constraints which would put the security of the SPC at risk.

6.2 Developed scheme for Interconnection Power Flow control of a Smart Power Cell

The fundamental structure of the developed scheme is illustrated in figure 6.1.

On the left side of the figure, a schematic overview of an exemplary SPC is depicted. On the right side, the fundamental building blocks of the scheme are illustrated. Further, selected signals required for the control procedure are represented by dashed arrows.

The aim of the developed control scheme is to control the apparent IPF

$$\bar{S}_n^{\mathrm{IPF}} = P_n^{\mathrm{IPF}} + \mathrm{j}Q_n^{\mathrm{IPF}} \tag{6.1}$$

of a particular SPC n to follow the apparent IPF reference value

$$\bar{S}_n^{\mathrm{IPF,ref}} = P_n^{\mathrm{IPF,ref}} + \mathrm{j}Q_n^{\mathrm{IPF,ref}} \tag{6.2}$$

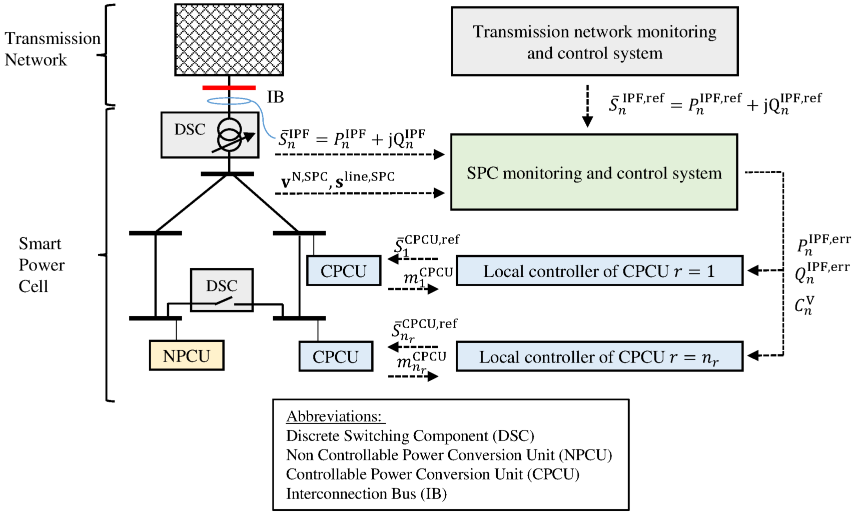


Figure 6.1: Fundamental structure of the developed control scheme for IPF control of an SPC

which is issued by the transmission system operator in case of need.

To achieve this goal, the active and reactive power behaviour of controllable PCUs connected within the SPC is controlled by local controllers (see Fig. 6.1). By controlling the active power output P_r^{CPCU} and the reactive power output Q_r^{CPCU} of the controllable PCUs which belong to an SPC, the IPF of that particular SPC can be influenced as the following equations show. The active IPF P_n^{IPF} of a particular SPC n can be expressed by

$$\begin{aligned} P_n^{\mathrm{IPF}} = \sum_{d \in D_n} P_d^{\mathrm{NPCU}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}, \mathbf{e}_n^{\mathrm{SPC}}) + \sum_{l \in L_n} P_l^{\mathrm{loss}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}) + \\ \sum_{r \in R_n} P_r^{\mathrm{CPCU}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}, \mathbf{e}_n^{\mathrm{SPC}}, \mathbf{c}_n^{\mathrm{SPC}}), \end{aligned} \tag{6.3}$$

where P_d^{NPCU} is the active power behaviour of the non-controllable PCU $d \in D_n$, P_l^{loss} is the active power loss of line $l \in L_n$ and P_r^{CPCU} is the active power behaviour of the controllable PCU $r \in R_n$. Here, D_n L_n and R_n are the sets of NPCUs, lines and CPCUs which belong to the SPC n.

The reactive IPF Q_n^{IPF} of a particular SPC n can be expressed by Eq. 6.4.

$$\begin{aligned} Q_n^{\mathrm{IPF}} = \sum_{d \in D_n} Q_d^{\mathrm{NPCU}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}, \mathbf{e}_n^{\mathrm{SPC}}) + \sum_{l \in L_n} Q_l^{\mathrm{loss}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}) + \\ \sum_{r \in R_n} Q_r^{\mathrm{CPCU}}(\mathbf{x}_n^{\mathrm{SPC}}, \mathbf{y}_n^{\mathrm{SPC}}, \mathbf{e}_n^{\mathrm{SPC}}, \mathbf{c}_n^{\mathrm{SPC}}) \end{aligned} \tag{6.4}$$

Here, Q_d^{NPCU} is the reactive power behaviour of the non-controllable PCU $d \in D_n$, Q_l^{loss} is the reactive power loss of line $l \in L_n$ and Q_r^{CPCU} is the reactive power behaviour of the controllable PCU $r \in R_n$.

Note here that the equations 6.3 and 6.4 are highly non-linear and interdependent. This is due to the fact that a change in P_r^{CPCU} or Q_r^{CPCU} also leads to a change in $\mathbf{x}_n^{\mathrm{SPC}}$ and $\mathbf{y}_n^{\mathrm{SPC}}$ (see also the non-linear equation 4.25) which in turn leads to changes in P_d^{NPCU}, Q_d^{NPCU}, P_l^{loss} and Q_l^{loss} for all $l \in L_n$ and all $d \in D_n$.

Due to the non-linearity and interdependency of equations 6.3 and 6.4, a closed loop structure was chosen to control the apparent IPF $\bar{S}_n^{\mathrm{IPF}}$ to follow the reference value $\bar{S}_n^{\mathrm{IPF,ref}}$. To this, a central monitoring and control system (green block of Fig. 6.1) collects measured data regarding the current state of the SPC. The measured data collected by this block includes the current IPF $\bar{S}_n^{\mathrm{IPF}}(t)$, the current voltage profile $\mathbf{v}^{\mathrm{N,SPC}}$ and the current apparent load flows $\mathbf{s}^{\mathrm{line,SPC}}$. Furthermore, the block gets the signal $\bar{S}_n^{\mathrm{IPF,ref}}$ which is issued by the monitoring and control system of the transmission system (grey block in Fig. 6.1).

Based on the collected data, the SPC monitoring and control system continuously determines the control deviations

$$P_n^{\mathrm{IPF,err}} = P_n^{\mathrm{IPF,ref}} - P_n^{\mathrm{IPF}} \tag{6.5}$$

and

$$Q_n^{\mathrm{IPF,err}} = Q_n^{\mathrm{IPF,ref}} - Q_n^{\mathrm{IPF}} \tag{6.6}$$

which are computed by comparing measured IPF values with the IPF setpoints issued by the TSO. Note that $P_n^{\mathrm{IPF,err}}$ and $Q_n^{\mathrm{IPF,err}}$ are discrete-time signals, that is, a sequence of samples over time.

These deviations are sent to local controllers (blue blocks of Fig. 6.1) which are assigned to each of the controllable PCUs connected within the SPC. The local controllers (see for a detailed description sections 6.5) integrate the deviations $P_n^{\mathrm{IPF,err}}$ and $Q_n^{\mathrm{IPF,err}}$ to generate apparent power reference values $\bar{S}_r^{\mathrm{CPCU,ref}}$ for the controllable PCU assigned to them.

Note that the CPCUs can only adjust their active and reactive power output within their current FOR. Thus, in case a local controller issues a setpoint outside the FOR of their assigned PCU, the unit in question adopts the closest operation point to the setpoint requested by the monitoring and control system without leaving its FOR. In order to avoid a wind-up behaviour of the integrator, the units which reach an operational limit send a signal to their local controllers so that the integration of the corresponding control deviation is blocked. This is described in detail in section 6.5.

By this structure, all the PCUs which have not reached an operational limit contribute to the overall control goal by adjusting their active and reactive power output as long as the control deviations $P_n^{\mathrm{IPF,err}} \neq 0$ or $Q_n^{\mathrm{IPF,err}} \neq 0$. If one PCU reaches the boundary of its FOR, then the apparent power output of this unit maintains its current value while the remaining PCUs continue adapting their apparent power output to contribute to the overall control goal until the IPF setpoint is achieved.

6.3 Limitation of control actions which would lead to violations of grid constraints

Changing the active and reactive power behaviour of PCUs, which can also be thought of as changing the value of the apparent behaviour vector $\mathbf{u}_n^{\mathrm{CPCU}}$, has a fundamental impact on the overall state of the SPC. A change in $\mathbf{u}_n^{\mathrm{CPCU}}$ leads to a change in almost all other SPC states as Eq. 4.25 suggests. Thus, a change in $\mathbf{u}_n^{\mathrm{CPCU}}$ to achieve $P_n^{\mathrm{IPF,err}} = 0$ or $Q_n^{\mathrm{IPF,err}} = 0$ can lead to a violation of grid constraints (e.g. line loading or voltage limits). This is in particular the case when, the IPF reference value $\bar{S}_n^{\mathrm{IPF,ref}}$ issued by the transmission system operator is outside the IPF-FOR of the SPC n (see section 5.1). To avoid this, the IPF control scheme was designed to enable only changes in $\mathbf{u}_n^{\mathrm{CPCU}}$ which do not cause any violation of operational grid constraints. This means that the control scheme will only follow the reference values $P_n^{\mathrm{IPF,ref}}$ and $Q_n^{\mathrm{IPF,ref}}$ if the changes required do not put the security and stability of the SPC at risk. To this, the local controllers get condensed information regarding the voltage and load flow state of the electric grid of the SPC by the signals C^{V} and C^{F}. Furthermore, each local controller gets information concerning the state of its associated CPCU by the signal $\mathbf{m}_r^{\mathrm{CPCU}}$.

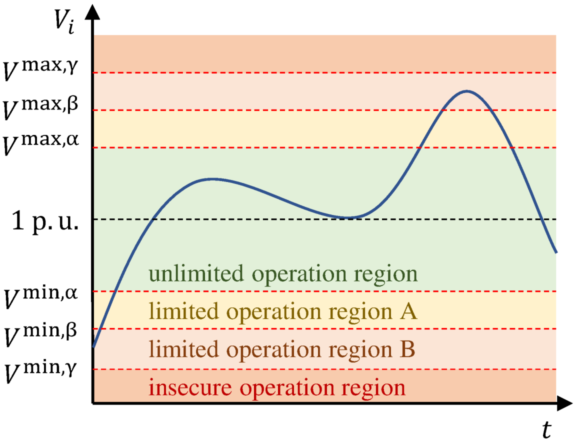


Figure 6.2: Voltage Limits and Operation Regions

6.4 Condensed description of the voltage state of a Smart Power Cell

Aiming to ensure the reliability and quality of supply, voltage magnitudes of SPC buses are required to stay within an acceptable voltage range. This has already been discussed in section 5.5.1 where it was stated that the voltage vector $\mathbf{v}^{\mathrm{n}}$ needs to remain within the space $\mathcal{V}^{\mathrm{SPC,Feasible}}$ which is defined by the set of inequality equations 5.17.

The same restriction can be expressed for each single bus $i \in I_n$ by

$$V^{\min,\gamma} \leq V_i(t) \leq V^{\max,\gamma}, \forall i \, \in \, I_n, \tag{6.7}$$

where $V^{\min,\gamma}$ and $V^{\max,\gamma}$ are predefined minimum and maximum tolerated bus voltage magnitudes and V_i is the voltage magnitude of a specific bus $i \, \epsilon \, I_n$. Here, I_n is the set of buses belonging to the SPC n.

The developed control scheme takes this fact into account and restricts changes that would lead to a voltage limit violation of any bus $i \in I_n$. To this end, six additional voltage boundaries, as depicted in Fig. 6.2, are introduced.

These limits ($V^{\min,\gamma}$, $V^{\min,\alpha}$, $V^{\min,\beta}$, $V^{\max,\alpha}$ $V^{\max,\gamma}$, $V^{\max,\beta}$) are used to describe the voltage situation of the SPC in a condensed way by the discrete state variable C^{V}.

The discrete state variable $C^{\mathrm{V}} \in \{-2, -1, 0, 1, 2\}$ is defined by

$$C^{\mathrm{V}}(k) = \begin{cases} 2 & \text{if}\, V_i \geq V^{\max,\gamma}, \exists i \in I_n \\ 1 & \text{if } C^{\mathrm{V}}(k-1) = 1 \wedge \\ & V^{\max,\gamma} \geq V_i \geq V^{\max,\alpha}, \exists i \in I_n \\ 1 & \text{if } C^{\mathrm{V}}(k-1) \neq 1 \wedge \\ & V^{\max,\gamma} \geq V_i \geq V^{\max,\beta}, \exists i \in I_n \\ 0 & \text{if } V^{\min,\alpha} < V_i < U^{\max,\alpha}, \forall i \in I_n \\ -1 & \text{if } C^{\mathrm{V}}(k-1) = -1 \wedge \\ & V^{\min,\gamma} \leq V_i \leq V^{\min,\alpha}, \exists i \in I_n \\ -1 & \text{if } C^{\mathrm{V}}(k-1) \neq -1 \wedge \\ & V^{\min,\gamma} \leq V_i \leq V^{\min,\beta}, \exists i \in I_n \\ -2 & \text{if}\, V_i \leq V^{\min,\gamma}, \exists i \in I_n \\ 0 & \text{else.} \end{cases} \tag{6.8}$$

To avoid that a local controller determines setpoints for a PCU that would lead to a violation of the overall voltage situation, the reference values $P_r^{\mathrm{CPCU,ref}}$ and $Q_r^{\mathrm{CPCU,ref}}$ are limited depending on the value of C^{V} which describes the overall voltage state of the SPC. Note here that the signal C^{V} is computed every 0.1 seconds and it is, therefore, a discrete time signal.

The state $C^{\mathrm{V}}(k)$ is zero when all voltage magnitudes V_i that belong to the set of measured voltages I_n are in the unlimited operation region (see Fig. 6.2). When the voltage of at least one node leaves the unlimited operation region, the discrete state $C^{\mathrm{V}}(k)$ may change depending on the trajectories of all voltage magnitudes which belong to I_n and the previous value of the state $C^{\mathrm{V}}(k-1)$ according to equation 6.8. Note that k denotes the current sampling period and $(k-1)$ the previous one. The use of this state variable by the local controller to restrict changes of $P_r^{\mathrm{CPCU,ref}}$ and $P_r^{\mathrm{CPCU,ref}}$ to prevent voltage limit violations is described in the next section.

6.5 Description of the local controllers

As illustrated in figure 6.1, each CPCU gets apparent power setpoints $\bar{S}_r^{\mathrm{CPCU,ref}}$ which are generated by a local controller. To this, a local controller is assigned to each CPCU. The block diagram of a local controller is depicted in Fig. 6.3.

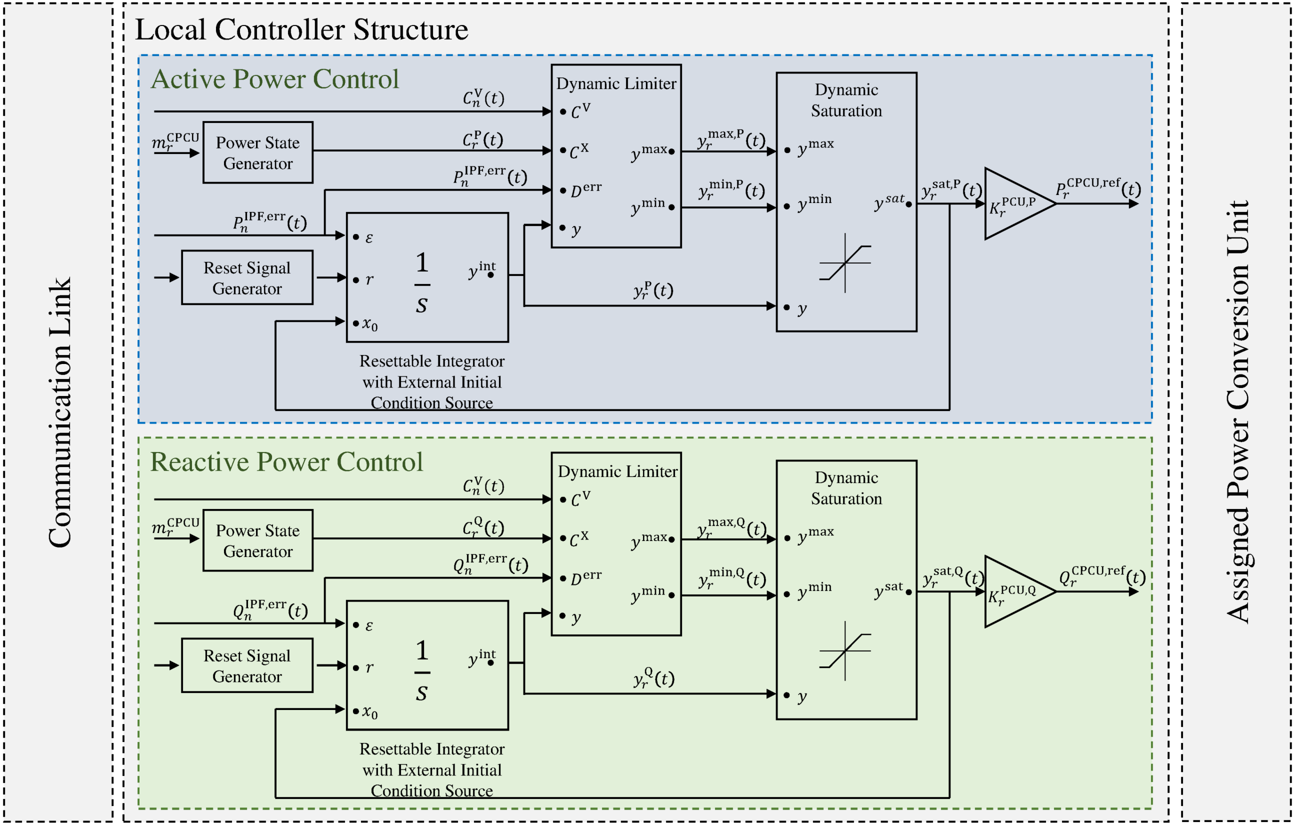


Figure 6.3: Local controller structure

A local controller is composed of two sub-controllers, which regulate independently the active and reactive power reference values $P_r^{\mathrm{CPCU,ref}}(t)$ and $Q_r^{\mathrm{CPCU,ref}}(t)$ of the CPCU r. Each sub-controller (active power controller and reactive power controller) of a local controller consists of six blocks: (i) *Power State Generator*, (ii) *Reset Signal Generator*, (iii) *Resettable Integrator with External Initial Condition Source*, (iv) *Dynamic Limiter*, (v) *Dynamic Saturation*, (vi) *Constant Gain*. The local controllers control the active and reactive power behaviour of PCUs under consideration of their time dependent FORs without engendering the local stability of the SPC while integral wind-up behaviour is avoided when saturations are active. The following subsections describe the function of the blocks which compose a sub-controller.

6.5.1 Power state generator

The FOR of the PCU controlled by a particular local controller is considered via the discrete state variables C_r^{P} and C_r^{Q}. These variables are computed by the block *Power State Generator* (Fig. 6.3). The discrete state C_r^{P} is a time-discrete signal determined every 0.2 seconds by

$$C_r^{\mathrm{P}}(t) = \begin{cases} 1 & \text{if } P_r^{\mathrm{CPCU,ref}} \geq P_r^{\mathrm{CPCU,max}} \\ 0 & \text{if } P_r^{\mathrm{CPCU,min}} < P_r^{\mathrm{CPCU,ref}} < P_r^{\mathrm{CPCU,max}} \\ -1 & \text{if } P_r^{\mathrm{CPCU,ref}} \leq P_r^{\mathrm{CPCU,min}}. \end{cases} \tag{6.9}$$

The discrete state C_r^{Q} is a time-discrete signal determined every 0.2 seconds by

$$C_r^{\mathrm{Q}}(t) = \begin{cases} 1 & \text{if } Q_r^{\mathrm{CPCU,ref}} \geq Q_r^{\mathrm{CPCU,max}} \\ 0 & \text{if } Q_r^{\mathrm{CPCU,min}} < Q_r^{\mathrm{CPCU,ref}} < Q_r^{\mathrm{CPCU,max}} \\ -1 & \text{if } Q_r^{\mathrm{CPCU,ref}} \leq Q_r^{\mathrm{CPCU,min}}. \end{cases} \tag{6.10}$$

The time-dependent limits $P_r^{\mathrm{CPCU,max}}$, $P_r^{\mathrm{CPCU,min}}$, $Q_r^{\mathrm{CPCU,max}}$ and $Q_r^{\mathrm{CPCU,min}}$ are provided by the CPCU r as a sub-vector of $\mathbf{m}^{\mathrm{CPCU}}$. These limits are determined according to the time depended FOR of the corresponding PCU. The determination of the FOR of a CPCU is described in section 5.1.

6.5.2 Reset signal generator

In order to avoid integral wind-up behaviour when the dynamic saturations are active, the output of the integrator needs to be reset and initialized at particular moments. To this aim, the block *reset signal generator* generates the switching signal $r \,\epsilon \{0, 1\}$, which is used by the resettable integrator to determine when the integrator needs to be reset. While the normal value of r is zero, the *rest signal generator* returns $r = 1$ at the moment in which at least one of the discrete signals C^{P}, C^{Q} and C^{V} changes its values, or a zero-crossing is detected in at least one of the continuous signals $P^{\mathrm{IPF,err}}$ and $Q^{\mathrm{IPF,err}}$.

6.5.3 Resettable integrator with external initial condition source

The core building blocks of a local controller are two resettable integrators with external initial condition sources (see Fig. 6.3), which integrate the control deviations $P_n^{\mathrm{IPF,err}}(t)$ and $Q_n^{\mathrm{IPF,err}}(t)$ according to

$$\frac{dx^{\mathrm{int}}}{dt} = \begin{cases} \varepsilon & \text{if } r = 0 \\ 0 & \text{if } r = 1, \end{cases} \tag{6.11}$$

$$y^{\mathrm{int}} = \begin{cases} x^{\mathrm{int}} & \text{if } r = 0 \\ x^{\mathrm{int}} = x_0 & \text{if } r = 1. \end{cases} \tag{6.12}$$

Here, ϵ is the control error which is integrated, x^{int} is the state variable of the resettable integrator, x_0 an external initial condition signal and r an external reset input. This setup is required in order to avoid an integral wind-up when the dynamic saturation block, which will be introduced below, is active.

6.5.4 Dynamic limiter

The dynamic limiter computes, depending on its inputs, the time-dependent limits y^{max} and y^{min}, which are used as an input by the dynamic saturation. The inputs of a dynamic limiter are the discrete state C^{V}, the discrete power state C^{X} corresponding to the PCU r and the control deviation D^{err}. Note that here, C^{V}, C^{X} and D^{err} are internal variables of the dynamic limiter. The outputs of a dynamic limiter are computed according to

$$y^{\mathrm{max}} = \begin{cases} x^{\mathrm{DL}}(k) & \text{if } D^{\mathrm{err}} > 0 \wedge C^{\mathrm{V}} = -1 \\ x^{\mathrm{DL}}(k) & \text{if } D^{\mathrm{err}} > 0 \wedge C^{\mathrm{X}} = -1 \\ \infty & \text{else} \end{cases} \tag{6.13}$$

and

$$y^{\min} = \begin{cases} x^{\mathrm{DL}}(k) & \text{if } D^{\mathrm{err}} < 0 \wedge C^{\mathrm{V}} = 1 \\ x^{\mathrm{DL}}(k) & \text{if } D^{\mathrm{err}} < 0 \wedge C^{\mathrm{X}} = 1 \\ -\infty & \text{else.} \end{cases} \tag{6.14}$$

Here, $x^{\mathrm{DL}}(k)$ is the state variable of the block and is defined by

$$x^{\mathrm{DL}}(k) = \begin{cases} x^{\mathrm{DL}}(k-1) & \text{if } D^{\mathrm{err}} < 0 \wedge C^{\mathrm{V}} = 1 \\ x^{\mathrm{DL}}(k-1) & \text{if } D^{\mathrm{err}} < 0 \wedge C^{\mathrm{X}} = 1 \\ x^{\mathrm{DL}}(k-1) & \text{if } D^{\mathrm{err}} > 0 \wedge C^{\mathrm{V}} = -1 \\ x^{\mathrm{DL}}(k-1) & \text{if } D^{\mathrm{err}} > 0 \wedge C^{\mathrm{X}} = -1 \\ y & \text{else} \end{cases} \tag{6.15}$$

where $x^{\mathrm{DL}}(k)$ is the current value of x^{DL} and $x^{\mathrm{DL}}(k-1)$ is the value of the previous sampling period.

6.5.5 Dynamic saturation

The block *dynamic saturation* bounds the range of its input signal $y(t)$ to the upper and lower saturation values $y^{\max}(t)$ and $y^{\min}(t)$. These boundaries are determined by the block *dynamic limiter* depending on the state of the PCU r and the state of the network n. The output of the block *dynamic saturation* is defined by

$$y^{\mathrm{sat}}(t) = \begin{cases} y^{\max} & \text{if } y \geq y^{\max} \\ y & \text{if } y^{\min} < y < y^{\max} \\ y^{\min} & \text{if } y \leq y^{\min}. \end{cases} \tag{6.16}$$

Due to this block, changes of the reference values $P_r^{\mathrm{CPCU,ref}}(t)$ and $Q_r^{\mathrm{CPCU,ref}}(t)$ that would lead to a violation of limits can be blocked, while changes that do not put the security of the SPC at risk are still permitted.

6.6 Case study and simulation results

In this section, selected simulation results are presented in order to demonstrate the control scheme described in the previous sections. To this, in section 6.6.1, a test system which was developed to design and test control schemes of SPCs by mean of time domain simulations is described. Then, in section 6.6.2 the dynamic behaviour of the test system under consideration of the developed IPF control scheme is demonstrated.

6.6.1 Dynamic distribution network test system developed to design and test control schemes of Smart Power Cells

In order to design and test SPC control schemes, a distribution test system was developed. The system can be used to study the dynamic behaviour of an SPC by means of time-domain simulations. The test system builds upon the European configuration of the medium voltage distribution benchmark network described in [13] which was extended by a set of controllable and non-controllable PCUs including conventional and flexible loads, distributed generators and storage devices. The fundamental structure of the test system is illustrated in Fig. 6.4.

As Fig. 6.4 shows, the test system is composed of two feeders: feeder 1 consists of 11 (20 kV) buses interconnected by 12 lines and cables. Feeder 2 consists of three buses interconnected by two lines. The system incorporates three circuit breakers. Depending on their switching state, the test grid can be operated in a radial or in a meshed way. Each feeder is connected to the transmission network via an OLTC transformer which can adopt 17 tap positions. The OLTCs enable the exchange of active and reactive power between the transmission network and the feeders of the test system which are operated at medium voltage level.

To perform time-domain simulations, the developed test system has been implemented in Simulink using build-in models which can be found in the Simscape Power System library [63] (e.g. lines, synchronous machine) in combination with own implementations (e.g. distributed generators, storages, controllers). The OLTC transformers which interlink the SPCs with the transmission network are modelled combining three multi-winding transformer models (Simscape Power Systems library [63]) with an OLTC subsystem modelled with switches. The OLTC transformers are parametrized according to the European configuration of the medium voltage network benchmark described in [13]. The OLTCs are controlled to maintain the voltage at the low voltage side at 1 p.u. by measuring the voltage at the low voltage terminals of the transformer and changing its tap position when a deviation to the reference value is measured for more than four seconds. The transmission network is modelled as a Dynamic Thévenin equivalent. Conventional loads are modelled as impedance loads and induction motors which are modelled as in [43]. Flexible loads, controllable and non-controllable generators and storages are modelled according to the model structure described in [DM14] and [DM8].

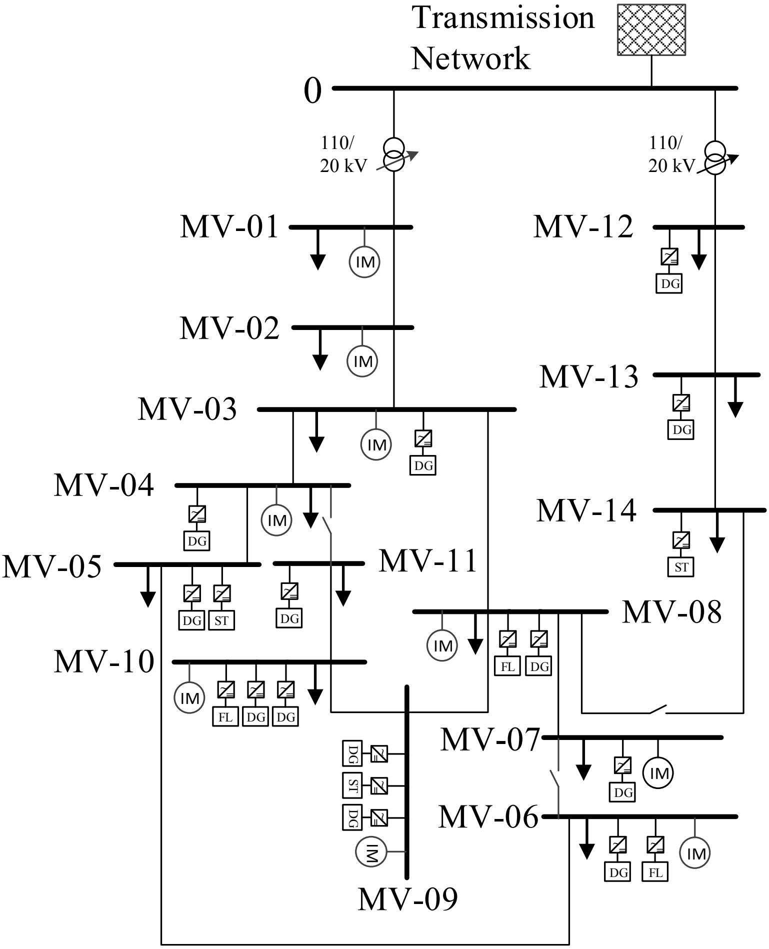


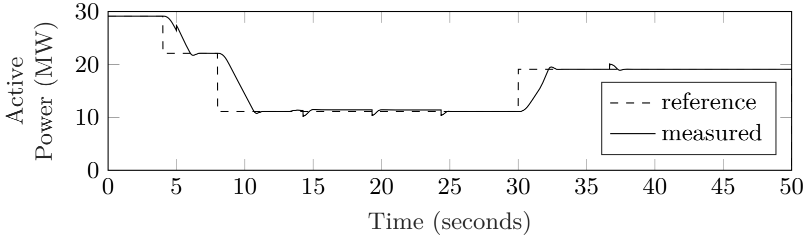
Figure 6.4: Distribution network configuration based on [13] used for modelling SPCs

The developed test system can be used to design and test SPC control schemes and analyse the dynamic behaviour of the test system. In the next section, selected simulation results are presented.

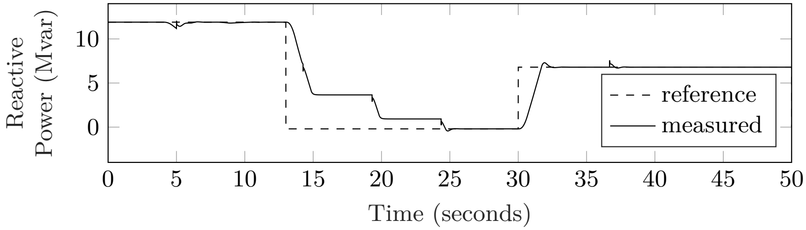
6.6.2 Case Study II: Demonstration of the developed scheme for controlling the Interconnection Power Flow of a Smart Power Cell

In this section, the dynamic behaviour of the test system described in section 6.6.1 taking into account the control scheme described in section 6.2 is studied. To this, selected signals which were obtained by a time-domain simulation are depicted in Fig. 6.5, Fig. 6.6 and Fig. 6.7. At the beginning of the simulation, the system is in steady-state and the SPC consumes $P^{\mathrm{IPF}} = 31.1\,\mathrm{MW}$ and $Q^{\mathrm{IPF}} = 12.8\,\mathrm{Mvar}$. This is shown by Fig. 6.5-a and Fig. 6.5-b, which depict the trajectories of the active and reactive interconnection power flows P^{IPF} and Q^{IPF} of the studied SPC. In addition, these figures illustrate the development of the power flow reference values $P^{\mathrm{IPF,ref}}$ and $Q^{\mathrm{IPF,ref}}$, which are adjusted by the control system of the TSO. The active and reactive power injection of an exemplary PCU (DG), which is connected to bus 11 of the test system, is illustrated by the figures 6.5-c and 6.5-d. Furthermore, to display how dynamic loads behave during the simulation, the active and reactive power consumption of an exemplary induction motor, which is connected to bus 7, is depicted in figures 6.7-a and 6.7-b. The voltage amplitudes of the High Voltage (HV) and Medium Voltage (MV) terminals of the OLTC transformer, which interfaces the studied SPC with the transmission network, are depicted in Fig. 6.6-b. The tap position of the studied OLTC transformer is shown in Fig. 6.6-a. Furthermore, Fig. 6.6-d shows the trajectory of the vector $\mathbf{v}^{SPC,amp}$, whose elements are the measured voltage amplitudes of the buses which belong to the studied SPC. In addition, the value of the discrete control variable C^{V} is given in Fig. 6.6-c.

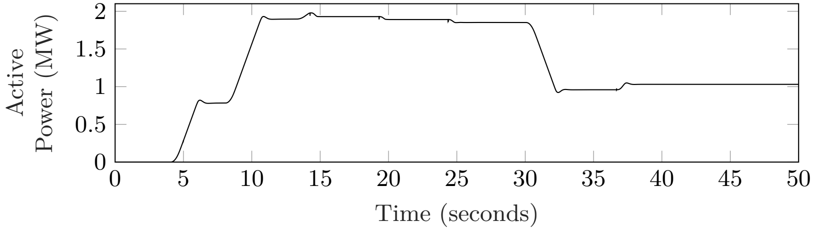
In this case study, the setpoint of the active IPF $P^{\mathrm{IPF,ref}}$ is changed three times and the setpoint of the reactive IPF $Q^{\mathrm{IPF,ref}}$ two times. At $t = 4\,\mathrm{s}$ and $t = 8\,\mathrm{s}$ the TSO requests a reduction of the interconnection active power flow P^{IPF} by changing the reference value $P^{\mathrm{IPF,ref}}$. Fig. 6.5-a shows that the SPC control scheme is able to regulate the power injection of the PCUs (see for example Fig. 6.5-c and Fig. 6.5-d) to follow the requested interconnection active power flow setpoints. As expected, the DG at bus 11 increases its active power injection (Fig. 6.5-c) from $t = 4\,\mathrm{s}$. Although the reactive IPF reference value $Q^{\mathrm{IPF,ref}}$ is kept constant between $t = 4\,\mathrm{s}$ and $t = 10\,\mathrm{s}$ (Fig. 6.5-b), the DG at bus



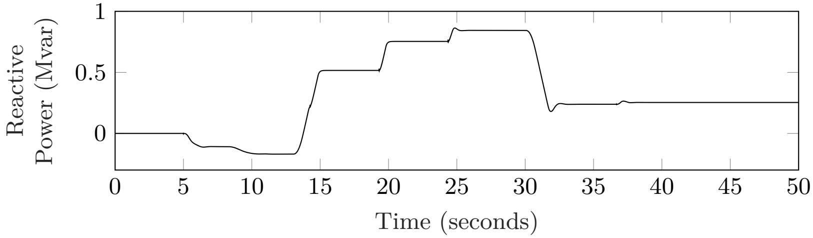
(a) Active Interconnection Power Flow of the studied SPC



(b) Reactive Interconnection Power Flow of the studied SPC

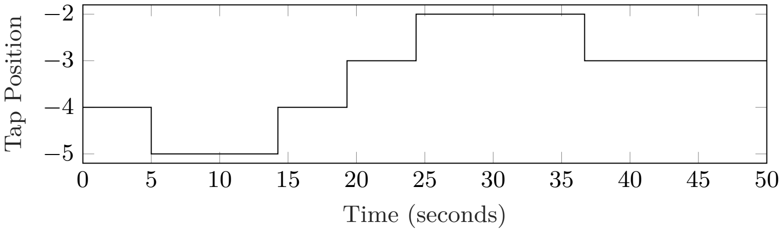


(c) Active power injected by an exemplary DG at bus 11 of the studied SPC

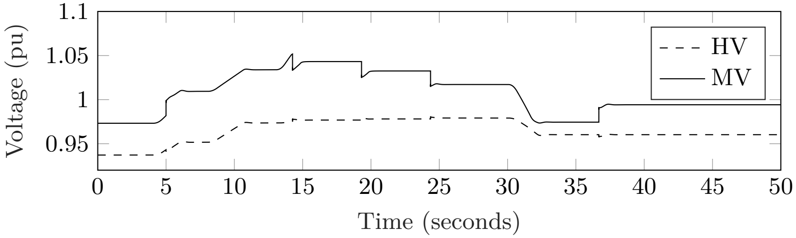


(d) Reactive power injected by an exemplary DG at bus 11 of the studied SPC

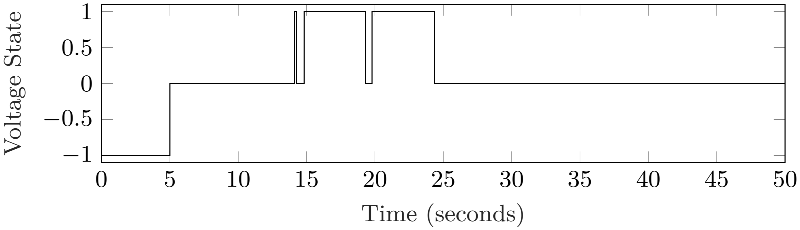
Figure 6.5: Case Study II - Controllability and performance study of an SPC with interconnection power flow control - Part I



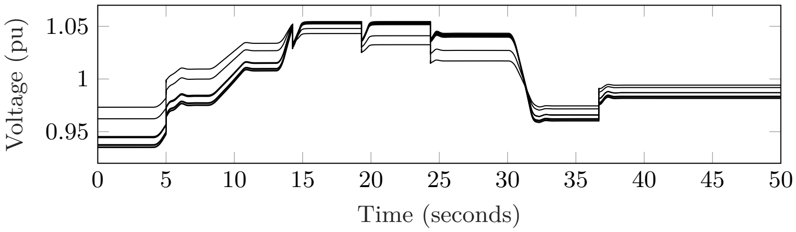
(a) Tap position of the OLTC of the transformer of the studied SPC



(b) Voltage amplitudes of the High Voltage (HV) and Medium Voltage (MV) terminals of the OLTC transformer of the studied SPC

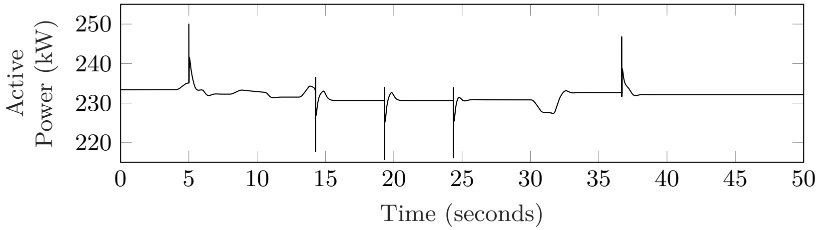


(c) Discrete control variable C^{V} of the studied SPC

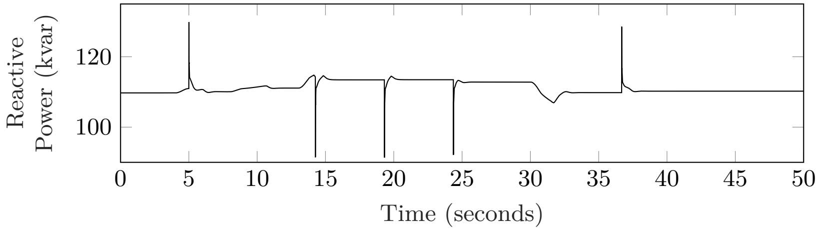


(d) Measured voltage amplitudes of the studied SPC

Figure 6.6: Case Study II - Controllability and performance study of an SPC with interconnection power flow control - Part II



(a) Active power consumption of an exemplary induction motor connected at bus 7 of the studied SPC



(b) Reactive power consumption of an exemplary induction motor connected at bus 7 of the studied SPC

Figure 6.7: Case Study II - Controllability and performance study of an SPC with interconnection power flow control - Part III

11 decreases its reactive power injection during this time interval (Fig. 6.5-d). This is due to the fact that when the active power injection of PCUs changes, the voltage profile in the distribution network also changes (Fig. 6.6-d), which in turn leads to a new load demand and loss profile. Thus, the SPC control scheme needs to compensate the new reactive power balance by the PCUs (see for example Fig. 6.5-d) in order to keep the interconnection reactive power flow Q^{IPF} constant as requested by the TSO (see Fig. 6.5-b).

The next simulated event is a change in the reference value $Q^{\mathrm{IPF,ref}}$ at $t = 13\,\mathrm{s}$ (Fig. 6.5-b) while the reference value $P^{\mathrm{IIPF,ref}}$ is kept constant (Fig. 6.5-a). As shown in Fig. 6.5-b, the SPC control first reduces the reactive IPF Q^{IPF} to reach the new setpoint, but at $t = 15\,\mathrm{s}$ its rate of change becomes $dQ^{\mathrm{IPF}}/dt = 0$. This is not an error, but a desired behaviour required to prevent the SPC control scheme from causing a voltage violation within the distribution network when it attempts to follow the requested interconnection power flow setpoint. This is due to the fact, that to reach the new setpoint $Q^{\mathrm{IPF,ref}}$, the PCUs are controlled to increase their reactive power output (Fig. 6.5-d) which leads to a rapid voltage increase between $t = 13\,\mathrm{s}$ and $t = 15\,\mathrm{s}$ (Fig. 6.5-d). At $t = 15\,\mathrm{s}$ however, the SPC control scheme detects a voltage violation. This is depicted in Fig. 6.6-c when $C^{\mathrm{V}} = 0$ becomes $C^{\mathrm{V}} = 1$. Consequently, the SPC control scheme blocks from that moment changes in the power injection of PCUs that would aggravate the voltage situation. Thus, the control scheme is able to approach the new setpoint without engendering the network security by transgressing the voltage limits (Fig. 6.6-d). It is important to mention, that in such a situation, the control scheme only blocks changes that aggravate the voltage problem, while changes that improve the local security are still permitted. Hence, from $t = 15\,\mathrm{s}$, the rate of change of the interconnection reactive power flow is kept $dQ^{\mathrm{IPF}}/dt = 0$ (Fig. 6.5-b), although the new setpoint has not been achieved. After four seconds, at $t = 19\,\mathrm{s}$, the OLTC transformer changes its tap position (Fig. 6.6-a) and thus relieves voltage situation within the SPC (Fig. 6.6-b and Fig. 6.6-d). Consequently, the control scheme detects that all bus voltages are again within the predefined voltage limits (Fig. 6.5-c) and allows changes in all directions. Hence, the reactive power injection of the PCUs can be further increased and thus, the reactive interconnection power flow Q^{IPF} can be further adjusted (Fig. 6.5-b) to approach $Q^{\mathrm{IPF,ref}}$ until at least one bus reaches a voltage limit once again (Fig. 6.5-b). This process continues, until the reference value $Q^{\mathrm{IPF,ref}}$ is met at $t = 25\,\mathrm{s}$ (Fig. 6.5-b).

The last simulated event in this case study, as Fig. 6.5-a and Fig. 6.5-b show, is when the TSO requests a simultaneous change in both, the active and reactive interconnection power flow at $t = 30\,\mathrm{s}$. The simulation shows that the control scheme is able to control the behaviour of the SPC and meets the requirements of the TSO (Fig. 6.5-a and Fig. 6.5-b).

Note that the tapping of the OLTC transformer at $t = 19\,\mathrm{s}$ and $t = 24\,\mathrm{s}$ (Fig. 6.6-a) leads to a transient adjustment process of the active and reactive power consumed by the dynamic loads (Fig. 6.7-e and Fig. 6.7-f). In this scenario, however the impact of this transient process does not have a major impact on the overall dynamic behaviour of the SPC .

6.7 Summary

In this chapter, a control scheme to control the IPF of an SPC has been presented. The developed scheme was designed to coordinate the behaviour of PCUs and DSCs of an SPC to control its IPF to follow reference values provided by the TSO or a superimposed control scheme. In particular, the scheme is able to simultaneously control the active and reactive IPF of an SPC without transgressing grid constraints, which was a novum in comparison to the state-of-the-art control schemes when the developed scheme was presented the first time in [DM14] and [DM12]. Such a control scheme could be used in the future to coordinate the behaviour of SPCs and by this integrate PCUs such as PV-units, wind energy converters, storages, flexible loads and multimodal interfaces connected at distribution networks in the operation of the transmission network. The developed scheme has been tested by means of time-domain simulations in a test system developed for this purpose. The simulations demonstrated that the scheme is able to coordinate the behaviour of the PCUs of the test system to follow the IPF reference values without causing voltage limit violations. However, in the simulations shown in this chapter, the behaviour of the transmission system has been modelled with a dynamic Thévenin equivalent. This simplification is suitable for development purposes or for testing control schemes under controlled conditions. However, before a new control scheme can be tested in the field, also its impact to the overall behaviour of the power system needs to be studied which implies that the interactions between the transmission and distribution domain need to be considered in detail. Besides, the behaviour of several SPCs interacting with each other via the transmission network needs also to be in the centre of attention to understand how future power systems organized according to the SPC concept will dynamically behave. To do so, a combined transmission-distribution test system is required. Such a test system is presented in the next chapter, where the behaviour of a future power system under consideration of several SPCs controlled as proposed in the previous sections is studied.

7 Dynamic behaviour of a power system organized according to the Smart Power Cell concept

The stable and reliable operation of an electric power system relies on comprehensive control strategies for the regulation and coordination of a large number of interacting dynamic subsystems such as power plants, electric networks, OLTC transformers, distributed generators and loads. When new control strategies or structural changes are planned, the consequences of those interventions cannot be tested directly on the field without a thorough understanding of how those changes would impact the behaviour and safety of the system. To this, static and time-domain simulations can be conducted to study the behaviour and stability of the system in advance, taking the newly developed control strategies and planned structural changes into account. Thus, the effects of adapting the infrastructure or implementing new control schemes can be investigated without actually implementing these changes in reality, which could cause irreparable damages to the system.

In this chapter, as a contribution to the development of the SPC concept, first, a combined Transmission-Distribution test system, which was developed to design and test control schemes for a future power system organized according to the SPC concept, is described in section 7.1. The test system, which has been implemented in Matlab Simulink, can be used to perform time-domain simulations in normal but also contingency situations under consideration of new control schemes. In particular, the model contains a detailed description of both, the transmission and the distribution domain, such that cross voltage level interactions can be studied. This is, in particular, necessary when cross-voltage-level control schemes need to be designed and tested, making the developed test system ideal for studying control schemes related to the SPC concept. A mathematical model for this purpose has already been described in section 4.4. In section 7.1 a specific implementation of such a model is described. The developed test system is composed of a transmission network, five conventional distribution network and 8 SPCs which are controlled with the scheme that was described in section 6.

In order to demonstrate the performance of the developed test system, in this chapter, two selected case studies are presented which aim to demonstrate how a power system organized according to the SPC concept would dynamically behave if the behaviour of its SPCs is coordinated by a superimposed monitoring and control system to support the operation of the transmission network.

In case study III-a (section 7.2) it is shown how the SPCs of the developed test system are coordinated to solve a congestion at transmission network level. In this case study, the monitoring and control scheme of the transmission network detects that one of the transmission network lines is overloaded and issues IPF setpoints for its SPCs to solve the problem. Subsequently, the SPCs adapt their IPFs by controlling their PCUs [9] and meet the setpoints provided by the TSO. The simulation results show that the power flow of the overloaded line can be reduced by 10 % by coordinating the behaviour of the SPCs.

Further, in case study III-b (section 7.3), the impact of a short circuit on the dynamic behaviour of the test system is investigated. In this case study, a short circuit, which is cleared after 200 ms, is simulated. However, after the fault is cleared, a power plant remains isolated causing under-voltages on several buses of the test system. In addition, the case study also demonstrates how these voltage problems can be improved by coordinating the behaviour of the SPCs connected to the system.

Note that the test system and the case study III-a presented in this chapter has already been described in previous work [DM9].

7.1 Combined transmission-distribution test system for designing and testing cross-voltage-level control schemes

This section describes the test system which was developed to study the dynamic behaviour of a power system organized according to the SPC concept. The test system, which is modelled as proposed in section 4.4, is composed of one transmission network, five conventional distribution networks and eight SPCs. The fundamental structure of the test system is illustrated in figure 7.1.

The transmission network of the test system is based on the European configuration of the high voltage transmission network benchmark described in [13]. It consists of 12 buses interconnected by seven high voltage (220 kV) and one extra high voltage (380 kV) lines which are modelled using the build-in 3-phase PI section line model available in the Simscape Power Systems library [63]. This configuration was chosen due to the fact that it is complex enough to model and

---

[9] The term Power Conversion Unit (PCU) has been introduced in section 3.2. A PCU is a component of the power system that converts energy from one of its forms (e.g. mechanical, thermal, chemical) into electric energy or vice versa by capturing energy from one system and releasing it into another system by means of a power flow. In this dissertation, distributed generators, storages, flexible loads and multimodal interfaces are considered to be PCUs.

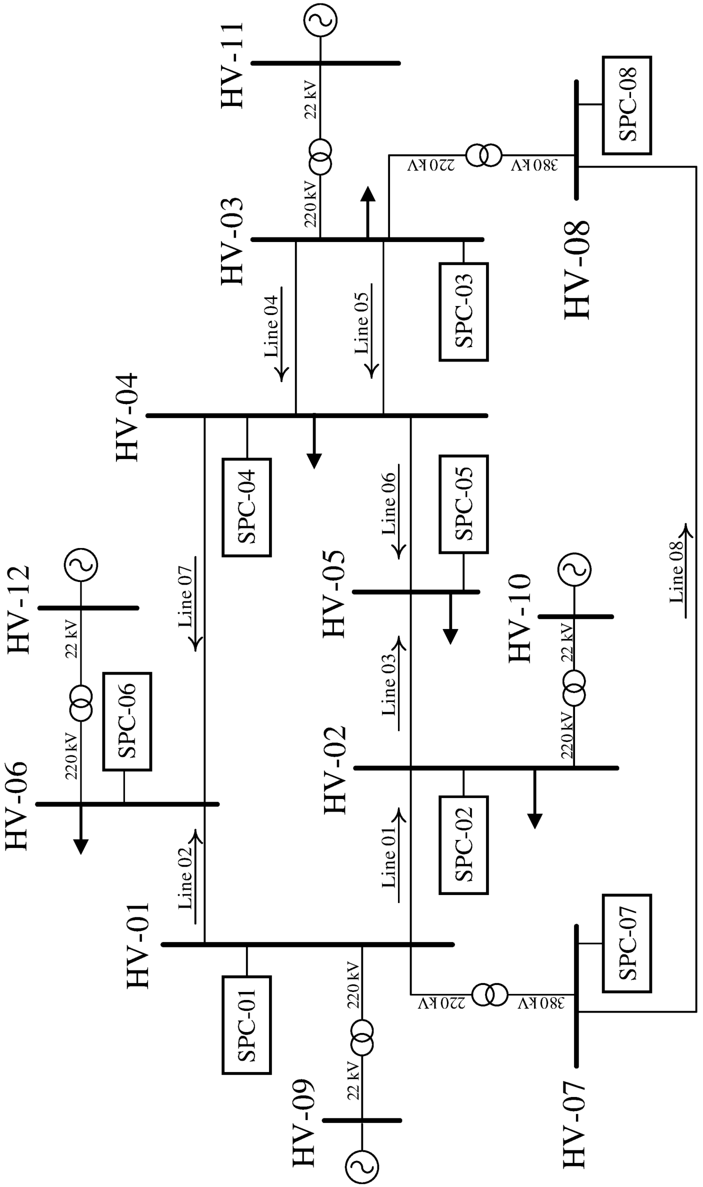


Figure 7.1: Modified European high voltage Cigre benchmark network

study several dynamic phenomena which could occur in a real power system (e.g. inter-area oscillations, frequency instability, voltage instability, angle instability) while its limited size enables the traceability of the system's behaviour. This is in particular required when new concepts and control schemes are developed.

In total, four conventional power plants (synchronous generator based) operating at 22 kV nominal voltage are connected to the transmission network. The power plants connected to the buses HV-09 and HV-10 are thermal plants, those connected to the buses HV-11 and HV-12 are hydro plants. The conversion of mechanical to electrical power is realised with a synchronous generator (Simscape sixth-order build-in model [63] parametrized based on [13] and [54]) which feeds active and reactive power to the system via a step-up transformer, which is used to increase the voltage from the generation level (22 kV) to the transmission level (220 kV). Each power plant is equipped with a turbine and prime mover controller (modelled and parametrized based on [45]) as well as an automatic voltage regulator and a power system stabilizer (Modelled and parametrized based on [46]). All power plants are controlled to keep the voltage at the connection point at 1 p.u..

The distribution domain of the test system consists of five passive distribution networks and eight SPCs all connected to buses of the transmission network (see figure 7.1). Passive distribution networks are modelled as impedance loads connected via an OLTC transformer to particular buses of the transmission network. SPCs are modelled in detail based on the European configuration of the medium voltage distribution network benchmark described in [13] and controlled by the control scheme described in section 6. The SPC models are identical to the dynamic implementation of an SPC described in section 6.6.1 (see also figure 6.4) with the distinction that here, the OLTCs are not connected to a Thévenin equivalent but to particular buses of the transmission network model of the combined Transmission-Distribution test system. All SPCs have the same network topology (see figure 6.4) and only differ by the number and location of generators, storages and loads connected to them.

The test system was implemented in Matlab Simulink using build-in models which can be found in the Simscape Power System library [63] (e.g. lines, synchronous machine) in combination with own implementations [DM8, DM14] (e.g. distributed generators, storages, controllers). The system comprises detailed models of conventional power plants, conventional and flexible loads, storages, distributed generators, OLTC transformers, circuit breakers, electric lines, measurement equipment and monitoring and control systems. ICT-processes are modelled as described in section 4.4.6. The impact of the environment on the behaviour of the system is modelled in form of time series as described in 4.4.5.

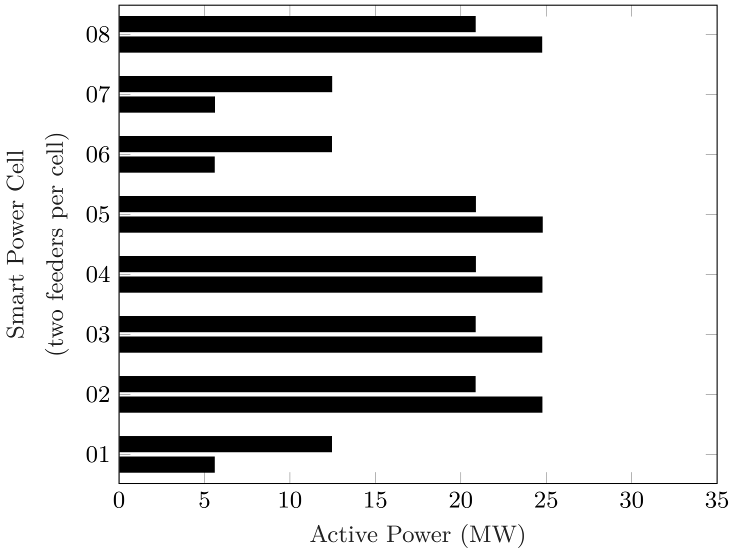
7.2 Case study III-a: Coordination of Smart Power Cells for power flow reduction of overloaded transmission network line

This section presents the simulation results of a case study which has been selected to demonstrate the behaviour of the test system described in section 7.1 when its SPCs are requested to support the operation of the transmission network. The simulation shows how the SPCs adjust their IPFs following setpoints provided by the monitoring and control system of the transmission network such that the power flow of the overloaded transmission network line 08 (see Fig. 7.1) can be reduced.

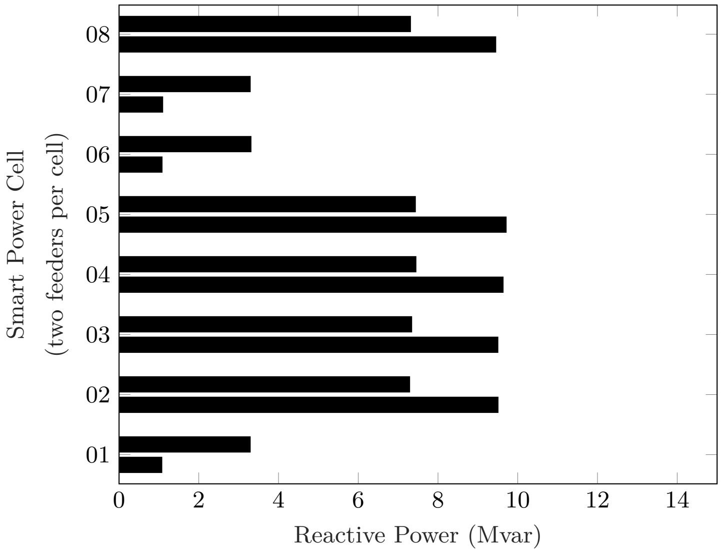
In the selected example, the apparent power flow of line 08 is reduced by controlling the active IPF of the SPCs connected to the system while their reactive IPFs are requested to stay constant. This "simple" example was selected in order to demonstrate the behaviour of the system while enabling a straight forward traceability of causes and effects. However, it should be noted that more complex control scenarios (e.g. simultaneous changes of active and reactive IPFs) are possible as extensive simulations have demonstrated.

7.2.1 Scenario set up

An overview of selected quantities which describe the state of the test system at the beginning of the conducted time-domain simulation (case study III-a) is presented in the figures 7.2 and 7.3. The simulation starts in steady-state with a total conventional power injection of 1534 MW active and 607 Mvar reactive power and a total - residual - load at transmission network level of 1445 MW active and 593 Mvar reactive power. The total - residual - load at transmission network level is the total power consumed by conventional distribution networks and SPCs measured at their interfaces with the transmission network. The difference between power injected by conventional power plants at transmission level and the total - residual - load results due to transmission losses over the transmission network lines. Around 18 % of the active and 16 % of the reactive residual system load is consumed by SPCs and the rest by conventional distribution networks. Distributed generators connected to SPCs inject at the beginning of the simulation in total 81 MW active and 24 Mvar reactive power. The initial active and reactive IPFs of the SPCs are illustrated in Fig. 7.2-a and Fig. 7.2-b.

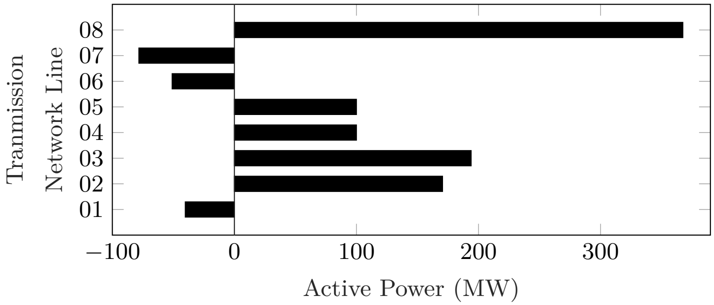


(a) Active IPF of the SPCs at $t = 0$

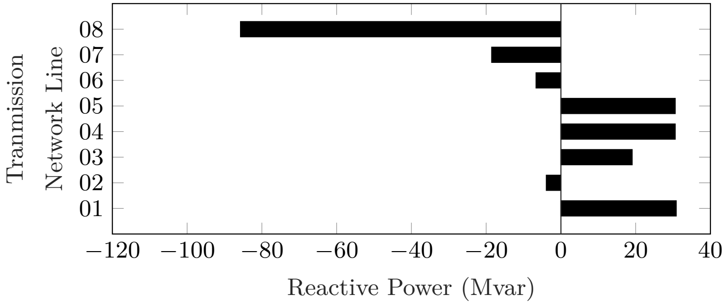


(b) Reactive IPF of the SPCs at $t = 0$

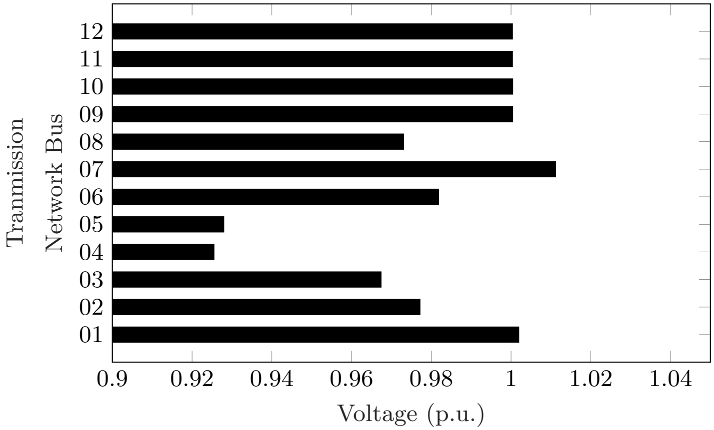
Figure 7.2: Case study III-a: Initial IPFs of SPCs



(a) Active power flow over transmission network lines at $t = 0$ (measured at beginning of line)



(b) Reactive power flow over transmission network lines at $t = 0$ (measured at beginning of line)



(c) Voltage amplitudes of transmission network buses at $t = 1$

Figure 7.3: Case study III-a: Initial power flows over transmission network lines and voltage amplitudes of transmission network buses

The initial active and reactive power flows over the lines of the transmission level are depicted in Fig. 7.3-a and Fig. 7.3-b. The figures show that the transmission line 08 carries an apparent power flow of 376 MVA (367 MW - j 85 Mvar). The corresponding initial voltage profile at transmission network level is given by Fig. 7.3-c. As can be expected, the voltage amplitudes of the buses at which conventional power plants are connected (HV-09, HV-10, HV-11 and HV-12) are 1 p.u.. This is due to the implemented automatic voltage regulator of the conventional power plants. All other transmission network voltage amplitudes are within a feasible range.

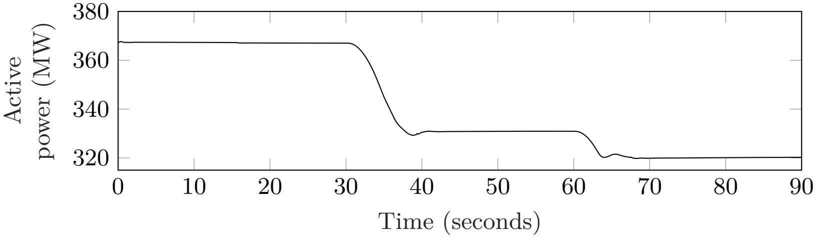
7.2.2 Time domain simulation

This section presents the simulation results of case study III-a for a time interval of 90 seconds. Selected signals obtained by the simulation are depicted in figures 7.4, 7.5, 7.6 and 7.7.

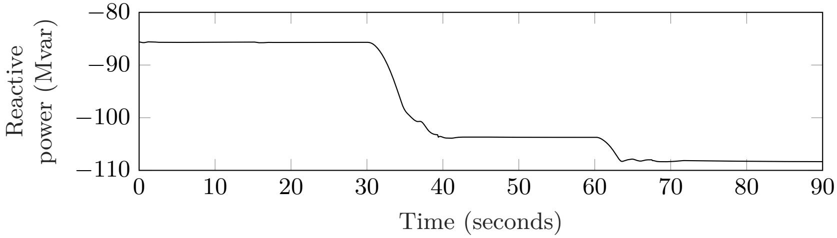
In this case study, the monitoring and control system of the transmission network issues active and reactive IPF setpoints for all the SPCs connected to it. The goal is to reduce the apparent power flow over the transmission network line 08 of the test system (Fig. 7.1) by 10 %. This is done in two stages: the first setpoint change takes place at $t = 30\ s$ and the second at $t = 60\ s$. For traceability purposes, the setpoints of all SPCs are changed simultaneously. As the trajectories of the active and reactive power flow over line 08 show (Fig. 7.4-a and Fig. 7.4-b), controlling the IPF of the SPCs leads to the desired result: At the end of the simulation, line 08 carries an apparent power flow of 337 MVA (320 MW - j 108 Mvar), which represents a reduction of 10 % in comparison to its previous value of 376 MVA (367 MW - j 85 Mvar).

The changes of the IPFs of SPCs also have an impact on the voltage profile at transmission network level. This is depicted in Fig. 7.4-c and Fig. 7.4-d which show the trajectories of the voltage amplitude of two exemplary transmission network buses. While the voltage of bus HV-08 (Fig. 7.4-c) significantly changes during the simulation time, the voltage of bus HV-10 remains almost constant (Fig. 7.4-d). This results from the fact that the voltage of bus HV-10 is controlled by the automatic voltage regulator of the power plant which is connected to it (see also figure 7.1).

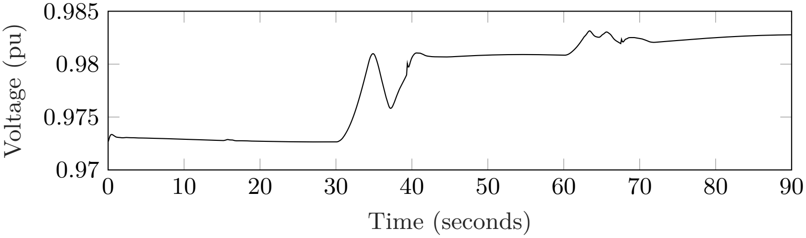
To achieve these changes at transmission network level, the monitoring and control system of the transmission network issues setpoints for the IPFs of all modelled SPCs two times. The trajectories of the active IPF of two exemplary SPCs are depicted in Fig. 7.5-a and Fig. 7.6-a.



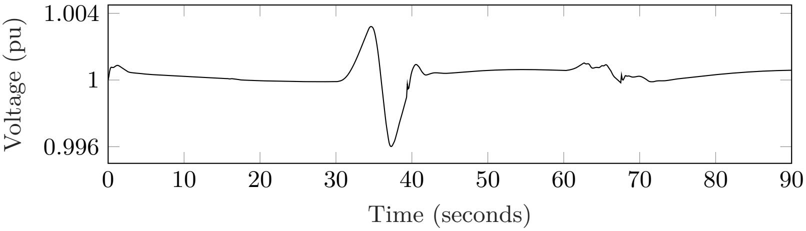
(a) Active load flow over transmission network line 08 measured at the beginning of the line



(b) Reactive load flow over transmission network line 08 measured at the beginning of the line

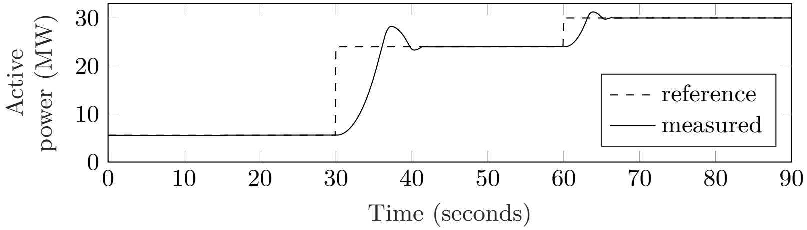


(c) Voltage amplitude of transmission network bus HV-08

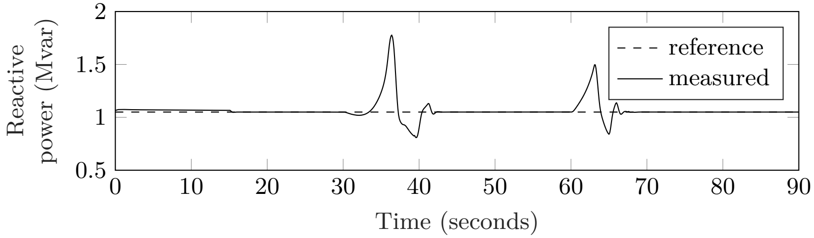


(d) Voltage amplitude of transmission network bus HV-10

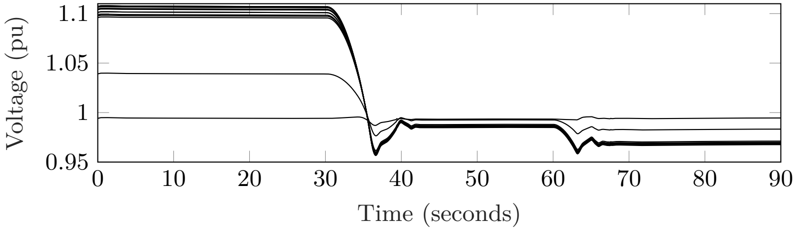
Figure 7.4: Case study III-a: selected simulation results - Part I



(a) Active IPF of feeder 01 of SPC 01

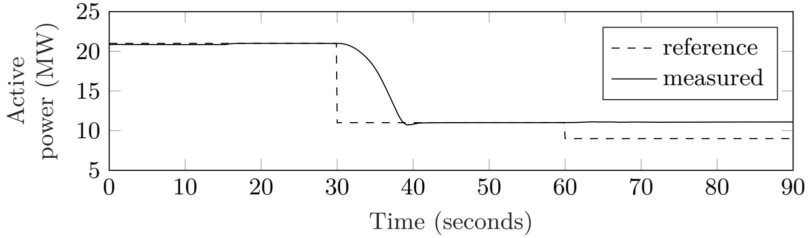


(b) Reactive IPF of feeder 01 of SPC 01

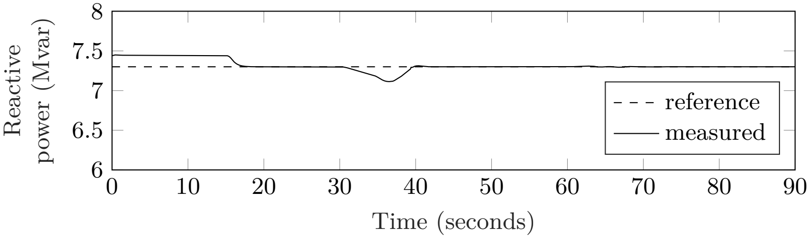


(c) Voltage amplitudes of buses belonging to feeder 01 of SPC 01

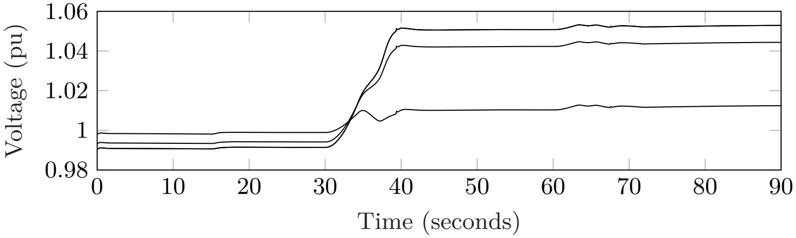
Figure 7.5: Case study III-a: selected simulation results - Part II



(a) Active IPF of feeder 02 of SPC 04

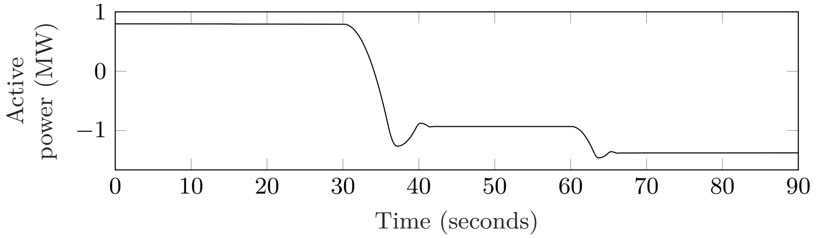


(b) Reactive IPF of feeder 02 of SPC 04

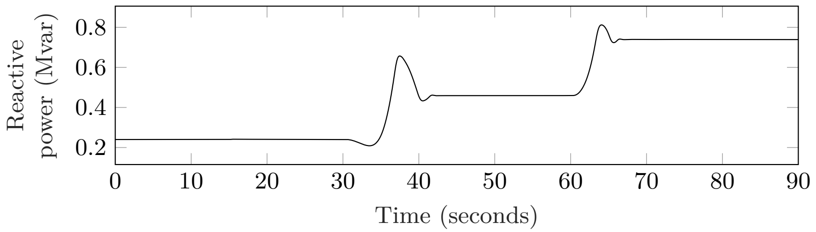


(c) Voltage amplitudes of buses belonging to feeder 02 of SPC 04

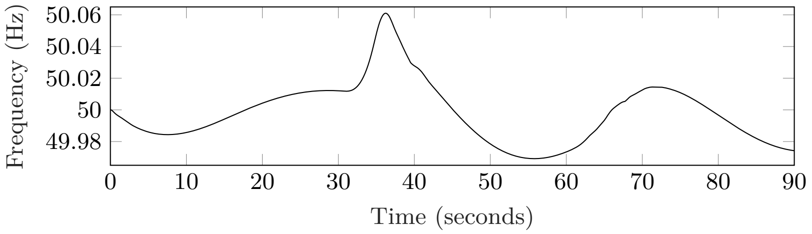
Figure 7.6: Case study III-a: selected simulation results - Part III



(a) Active power injection of storage device connected to bus 05 of feeder 01 of SPC 01



(b) Reactive power injection of storage device connected to bus 05 of feeder 01 of SPC 01



(c) Frequency measured at transmission network bus 10

Figure 7.7: Case study III-a: selected simulation results - Part IV

As desired, the control scheme is able to control the behaviour of the controllable PCUs within the SPCs such that the requested behaviour is achieved. Note that the IPF setpoints issued by the superimposed control system are illustrated by dashed lines. Further, the trajectories of the reactive IPF of this two selected SPCs is depicted in Fig. 7.5-b and Fig. 7.6-b. The figures show that the SPC control scheme is able to keep the reactive IPF nearly constant during the whole simulation time. The deviations between measured and reference values after IPF setpoint changes result from the active and reactive power coupling in the SPC: When the active power injection of PCUs is adjusted, this has an impact on the voltage profile of the SPC buses (e.g. see Fig 7.5-c and Fig. 7.6-c). Due to this fact, the reactive power consumed by loads and the reactive power losses also change. As a result, changing the active power injection by power conversion units within the SPC also leads to a change in the corresponding reactive IPF. Due to this, in order to keep the reactive IPF constant, the reactive power injection of power conversion units needs to be adjusted as well. This is depicted in Fig. 7.7-a and Fig. 7.7-b, which show the active and reactive power injection of an exemplary storage device connected to bus MV-05 of the SPC 01 (see Fig. 6.4). The figures depict how the SPC control system controls the behaviour of the storage device to reduce its active power injection in order to increase the active IPF of the SPC. Simultaneously, the reactive power injection of the storage is increased (Fig. 7.7-b), such that the augmented reactive power losses over the lines of the SPC are compensated and the reactive IPF can be kept constant (Fig. 7.5-b). Changes of the active and reactive power injections within an SPC have an impact on its voltage profiles. This can be observed in Fig. 7.5-c, which depicts the voltage amplitude trajectories of the buses of feeder 01 of the SPC 01. The figure shows that the buses remain during the whole simulation time within the pre-established voltage range of ±12 %.

Not all setpoints issued by the superimposed monitoring and control system can always be followed by the SPCs. IPF changes are only possible if the available flexibility within the SPC is sufficient and the requested change would not lead to any operational limit violation. This has been thoroughly discussed in chapter 5 where a method for determining the flexibility of an SPC to control its active and reactive IPF has been presented. This can for example be observed when the active and reactive IPF trajectories of feeder 02 of SPC 04 (Fig. 7.6-a and Fig. 7.6-b) are examined. Fig. 7.6-a shows that SPC 04 is able only to follow the first setpoint change at $t = 30$. When the second active IPF setpoint is requested, the measured IPF remains constant. In this case, this is to a lack of flexibility within the cell since all CPCUs within that SPC are already operated at their operational limit.

Even though the system frequency is not at the spotlight of this case study, Fig. 7.7-c shows that also changes in frequency can be represented by the test system. This is, however, especially interesting when contingencies are simulated, which is not the case in this case study. Fig. 7.7-c shows that the simultaneous control of the eight SPCs has a slight impact on the system frequency, however, the frequency remains within an acceptable range during the entire simulation time.

7.3 Case study III-b: Short circuit at transmission network level and voltage support by Smart Power Cells

In order to investigate the dynamic behaviour of the test system described in section 7.1 when faults take place, several case studies have been conducted. In this section, the simulation results of a selected short circuit case study is presented.

The selected case study shows how the test system (Fig. 7.1) dynamically behaves before, during and after a three-phase short circuit. The short circuit takes place at t = 20 s at the transmission network bus HV-11. The fault is cleared after 200 ms. The simulation results show that after the fault is cleared, the voltage amplitudes of several transmission network buses (HV-03, HV-08, HV-04, HV-05) are below the pre-established lower voltage limit of 0.9 p.u.. This is due to the fact that after the fault is cleared, bus HV-11 remains isolated and is not reconnected. Thus, the conventional power plant connected to this bus (HV-11) cannot continue to control the voltage of its connection point by adjusting its reactive power injection. Furthermore, the active power which was injected by this power plant before the fault needs to be taken over by the remaining power plants after the fault. This leads to higher power flows over the transmission network lines which also cause higher voltage drops.

In addition to this, the simulation results also show how the voltage situation in the affected area can be significantly improved by controlling the IPFs of the SPCs connected to the test system. For traceability reasons, in this case study, only the reactive IPF of SPCs is changed while the active IPF is maintained constant.

In the next section, selected simulation results which correspond to the selected case study are presented.

7.3.1 Scenario set up

For simplicity, the same scenario setup described in section 7.2.1 was chosen for the case study presented in the next section. The test system and the loading scenario at the beginning of the simulation of case III-b is identical as in case III-a. In this scenario, however, it is assumed that the capacity of the transmission line 08 is sufficient to carry the initial power flow.

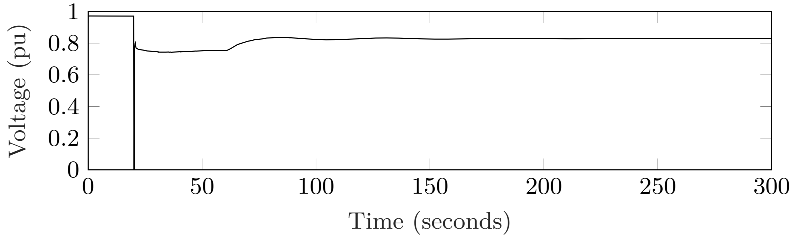
7.3.2 Time domain simulation

Selected simulation results of case study III-b are depicted in the figures 7.8, 7.9 and 7.10. All figures show trajectories of exemplary signals which were selected to describe the dynamic behaviour of the test system during a time period of 300 seconds. At the beginning of the simulation, the system is operated at steady-state and no operational limits are violated. At $t = 20$ s, a three-phase short circuit takes place at bus HV-11 of the test system (see Fig. 7.1). The short circuit is cleared after 200 ms, however, the bus HV-11 remains isolated after the fault is cleared. Thus, the power plant which is connected to it stops injecting active and reactive power into the transmission network. As a consequence, the voltages nearby bus HV-11 decrease significantly below the pre-established voltage limits.

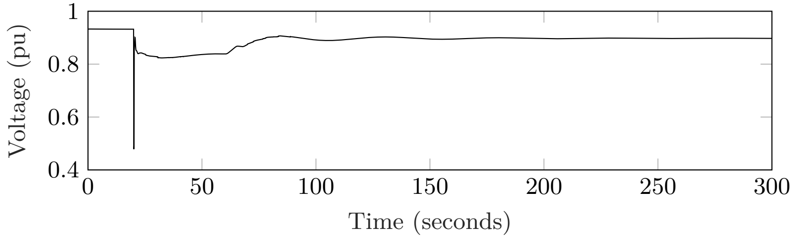
At $t = 60$ s, the monitoring and control system of the transmission network requests the support of the SPCs connected to the system by changing their control mode from $c^{\mathrm{SPC,mode}} = 6$ (IPFs of SPCs are not controlled) to $c^{\mathrm{SPC,mode}} = 1$ (IPFs of SPCs are controlled by TSO). The results show that by adjusting the reactive IPFs of the SPCs the voltage situation can be significantly improved.

Figure 7.8 depicts the trajectories of the voltage amplitudes of selected transmission network buses and the evolution of the frequency during the simulation time. The figures show that just after the short-circuit takes place, the voltages nearby the fault abruptly fall down and recover as soon as the fault is cleared. However, as the figures 7.8-a and 7.8-b show, after the fault is cleared the voltage amplitude of the buses HV-03 and HV05 is considerably below the value before the fault. This is not the case for bus HV-10 (Fig. 7.8-c) whose voltage amplitude remains within its limits and stabilizes at 1 p.u. This results from the fact that a conventional power plant is connected to this bus which controls its voltage by means of its automatic voltage regulator.

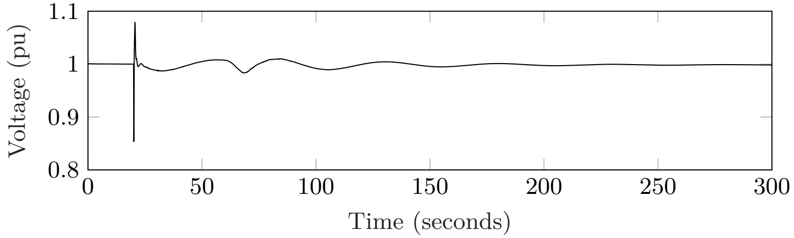
At $t = 60\ s$ the monitoring and control system of the transmission network request the support of SPCs to improve the voltage situation at transmission



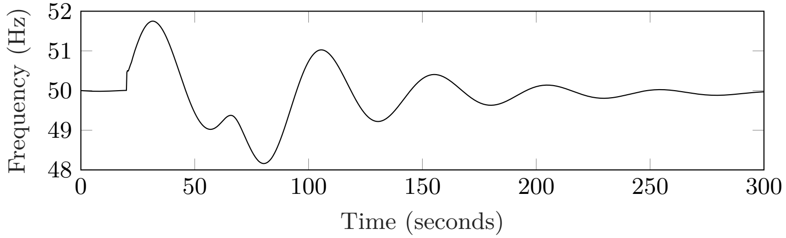
(a) Voltage trajectory of tranmission network bus 03 before and after a shortcircuit at transmission network bus 11



(b) Voltage trajectory of tranmission network bus 05 before and after a shortcircuit at transmission network bus 11

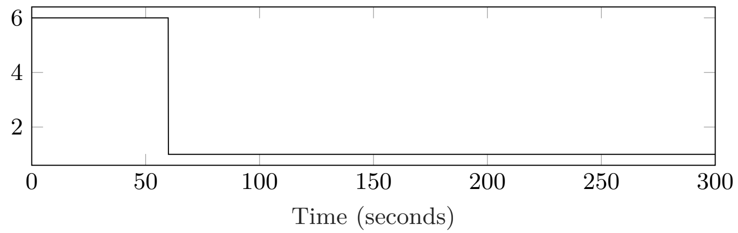


(c) Voltage trajectory of tranmission network bus 10 before and after a shortcircuit at transmission network bus 11

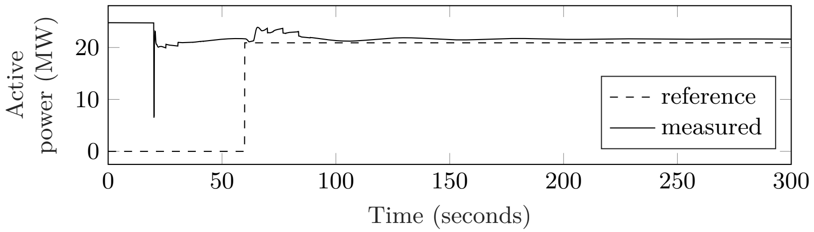


(d) Frequency measured at network bus 10 before and after a shortcircuit at transmission network bus 11

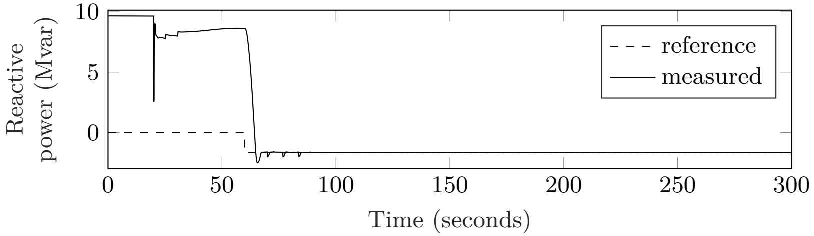
Figure 7.8: Case Study III-b: Selected signals to describe the behaviour of the transmission network before and after a short circuit at transmission network bus 11



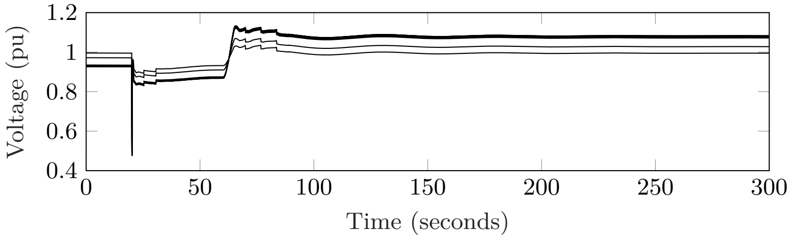
(a) [Control mode of feeder 01 of SPC 05



(b) Active interconnection power flow of feeder 01 of SPC 05

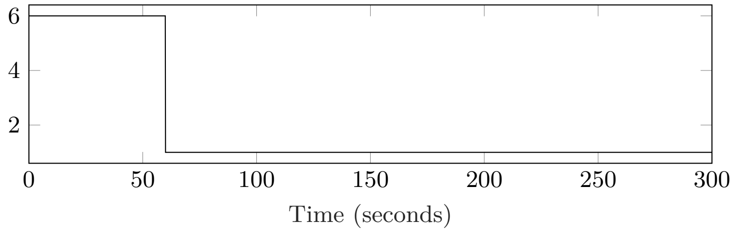


(c) Reactive interconnection power flow of feeder 01 of SPC 05

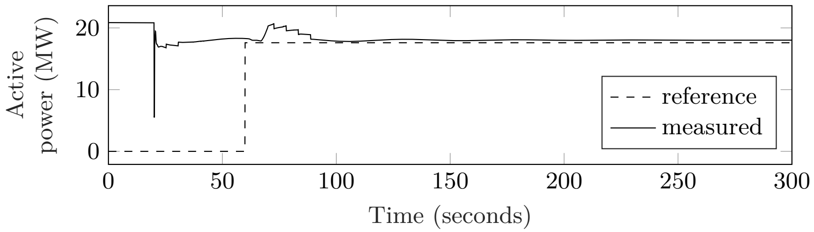


(d) Voltage amplitudes of distribution network buses of feeder 01 of SPC 05

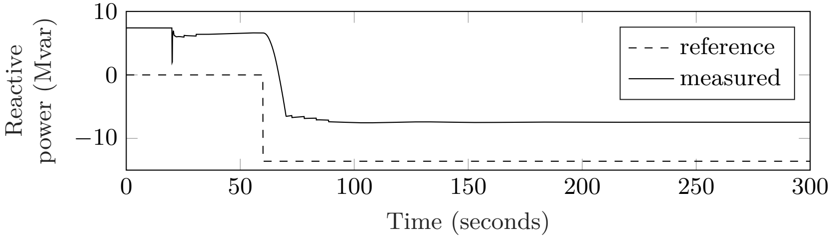
Figure 7.9: Case Study III-b: Selected trajectories of feeder 01 of SPC 05



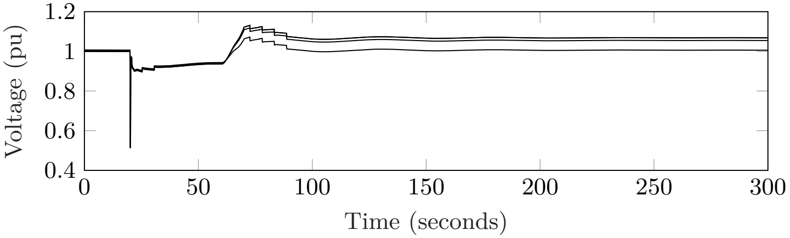
(a) Control mode of feeder 02 of SPC 05



(b) Active interconnection power flow of feeder 02 of SPC 05



(c) Reactive interconnection power flow of feeder 02 of SPC 05



(d) Voltage amplitudes of distribution network buses of feeder 02 of SPC 05

Figure 7.10: Case Study III-b: Selected trajectories of Feeder 02 of SPC 05

network level. Figure 7.8-a and figure 7.8-b show how after $t = 60s$ the voltage amplitude of the buses HV-03 and HV-05 increases due to the support of SPCs. Selected signals of feeder 01 and feeder 02 of the SPC 05 can be seen in figure 7.9 and figure 7.10. This SPC is connected to bus HV-05 of the transmission network (see figure 7.1). These figures show that, at the beginning of the simulation, the active and reactive IPFs of the SPC 05 are not controlled. This is because at the beginning of the simulation the control mode of the feeder 01 and 02 of SPC 05 is $c^{\mathrm{SPC,mode}} = 6$. For $c^{\mathrm{SPC,mode}} = 6$ the SPC can control its PCUs according to local needs and does not need to follow setpoints provided by the TSO. However, at $t = 60\ s$ the control mode of the SPC becomes $c^{\mathrm{SPC,mode}} = 1$. From this moment on, the SPC needs to be controlled according to the setpoints provided by the TSO. At the same time ($t = 60$ s), the TSO issues active and reactive IPF setpoints for feeder 01 (Fig. 7.9-b and 7.9-c) and feeder 02 (Fig. 7.10-b and 7.10-c) of SPC 05. From that moment, the control systems of the SPCs coordinate the behaviour of their PCUs to meet the setpoints and by this improve the voltage profile at transmission network. Note that here only the behaviour of one exemplary SPC is shown. However, to improve the voltage situation at transmission network level, in this case study, the behaviour of all SPCs connected to the system is simultaneously controlled. Figure 7.9-d and Figure 7.10-d show the voltage amplitudes of the buses which belong to feeder 01 and feeder 02 of the SPC 05.

7.4 Summary

In the previous sections, a combined transmission-distribution test system to study cross-voltage-level monitoring and control schemes of future power systems has been suggested. The test system was designed to develop and test methods and schemes which can be applied in a future power system organized according to the SPC concept by means of time-domain simulations. In addition, two selected case studies were presented. These case studies show examples of how the test system would dynamically behave if the control scheme to control the IPF of SPCs described in chapter 6 would be implemented to support the operation of the transmission network of the test system. The results shown here were selected to describe the fundamental behaviour of a system organized according to the SPC concept. However, the main contribution of this chapter is the test system and the developed simulation environment for time domain-simulation which can be used to further develop the controls schemes and methods presented in this dissertation and also develop and test new cross-voltage-level control methods. This is of fundamental importance since the operational concept and control schemes of current power systems need to be completely reviewed and redesigned if the goal of decommissioning conventional power plants is to be realized. By providing the developed test system and simulation environment, this dissertation intents to provide a foundation for the development of monitoring and control schemes for the operation of future power systems and in this manner make a contribution to the worldwide efforts to reduce CO_2 emissions and limit climate change. In the next chapter, the main conclusion and contributions of the dissertations are summarized. Further, an outlook on the required research to bring the SPC concept into life is provided.

8 Conclusions and outlook

In this dissertation, challenges related to the ongoing substitution of conventional power plants by distributed generators are discussed. In particular, the dissertation addresses the fact, that today, the operation of the system is based on the properties and capabilities of conventional plants which are planned to be decommissioned. In this context, it is still not clear how a future power system with a very high penetration of renewable generation will be operated. As an answer to this dilemma, the dissertation suggests a new system architecture and operational concept which is intended to enable an efficient, secure and stable operation of a future power system by enabling the participation of distributed generators, flexible loads, storages and multimodal interfaces in the operation of the system. The developed architecture and operational concept were conceived with the intention to organize and unify in a holistic and comprehensive way contemporary research efforts in the context of the decarbonisation of the electric sector. This dissertation, therefore, does not concentrate on single ancillary services, specific control problems or single components as it is usual in contemporary research. Instead, the operability, security and stability of the entire system in the context of its decarbonization is on the scope of study. By this, the dissertation provides a framework for further developments and is thus intended to contribute to the decarbonization of the electric sector.

8.1 Main contributions

As it has been stated in the introduction, this dissertation is intended to contribute to finding an answer to the following question:

> How can a future low-emission power system be structured, planned and operated so that its efficiency, security and stability can continue to be guaranteed when most conventional power plants - which today are the foundation for the operability and stability of the system - will no longer be in operation?

It should be noted, however, that it is not the aim of the dissertation to find a final solution to this dilemma or provide approaches which can be directly applied in the field. Instead, the dissertation seeks to formally describe related challenges and problems and provides a conceptual framework for further discussions and developments in the context of the decarbonization of the system. Besides, the dissertation describes prototypes of concepts and methods which can be applied in the context of planning, monitoring, control and simulation of future power systems. In the following, the main contributions of the dissertation are summarized.

C1: A comprehensive analysis of the importance of the properties and capabilities of conventional power plants for the efficient, secure and efficient operation of a power system has been conducted and consequences which could result due to their large-scale decommissioning have been identified. In particular, it has been discussed and explained why conventional power plants are essential for forming the grid (frequency and voltage). Besides, their role in congestion management, system optimization (e.g. reduction of losses) and system restoration after blackouts have been addressed. In addition, it has been discussed, why as today, tasks related to the operational and long term planning of power systems are mainly dedicated to the managing of the behaviours and capacities of conventional power plants. Based on these findings, it can be concluded that decommissioning conventional power plants without adapting the structure and operational concepts of the system, could endanger its operability and by this increase the risk of security violations and instability. The results of the analysis conducted can be thought of as a framework to define research objectives and requirements aimed to find solutions for the operation of future power systems under consideration of technical challenges which arise due to the decommissioning of conventional power plants.

C2: An architecture and operational concept which is intended to enable the efficient, secure and stable operation of a future power system has been developed and described. The developed architecture is founded on the idea of organizing the distribution network level of a future power system in supervised and controlled grid subsections called Smart Power Cells which are perceived from the perspective of the transmission network as single monitorable and controllable entities which can adapt their dynamic behaviour on demand. The concept aims at enabling that a future power system can be operated without the need for conventional power plants. To this, SPCs need to be integrated into the operation of the system in such a way that all interventions which today rely on the properties and capabilities of conventional power plants can be substituted. In this context, the main objectives and requirements which the monitoring and control system of an SPC needs to achieve have been described. In general, the monitoring and control system of an SPC needs to fulfil two types of control objectives: (i) Internal control objectives which are control aims related to enforcing a secure, stable and efficient operation of the cell itself and (ii) external objectives which are objectives required for the efficient, secure and stable operation of the entire power system. The external objectives are achieved by controlling the components of an SPC to impact its behaviour from transmission network perspective. In this context, the interface between the transmission network and an SPC has been described and important quantities for the description of the interaction of SPCs with the transmission network introduced. Finally, a cross voltage level coordination scheme has been suggested and the role of SPCs in the operation of a future power system discussed.

C3: The fundamental description of a mathematical model which can be used to study the dynamic behaviour of a power system organized according to the SPC concept has been presented. The model can be seen as an extension of the classic model which is usually used in practice and academia to study the behaviour of contemporary power systems. In fact, the methods used in this context (modelling of the system as a set of non-linear, algebraic-differential equations and using numerical integration for studying the evolution of states and other variables over time) do not really need to be modified. However, assumptions which are common practice today and were introduced in the past to reduce the complexity of the modelling task and to limit the computation expensiveness of conducting simulations are not admissible in the context of the SPC concept. As a solution to this problem, a model for a future power system organized according to the SPC concept has been suggested. In particular, the developed model is able to reproduce the dynamic interactions of a transmission network and its SPCs (the distribution network level). To this, not only the transmission network level is modelled in detail. Instead, the mathematical description of its SPCs, their components (Distributed generators, conventional and flexible loads, storages, multimodal interfaces, OLTC) and their associated control schemes are in the centre of attention. By this, the dynamic behaviour of a future power system organized according to the SPC concept, which in fact will be determined by the dynamic behaviour of its SPCs interacting among each other by means of the transmission network, can be studied and investigated.

C4: Two methods for determining the flexibility of an SPC to adjust its Interconnection Power Flow have been developed, described and tested. The first method can be used to determine the flexibility of an SPC under the premise of perfect information, i.e. when all modelled influencing factors are known. The second method, on the other hand, is meant to be used to estimate, in advance, the flexibility that an SPC will have in future time intervals. To this, forecasts of time-variant influencing factors are used and the associated uncertainty is considered by a probabilistic approach. In future, the developed methods could be used to determine and describe the flexibility of an SPC to support the operation of the transmission grid. Thus, TSOs could use this information during the operational planning of the system (e.g. day-ahead, intraday planning) and decide to what extent each SPC is required to contribute to the operation of the system.

C5: A control scheme for controlling the IPF of an SPC on demand has been developed, described and tested. The developed scheme is able to control the apparent behaviour of the PCUs connected within an SPC to control its IPF to follow set-points issued by the TSO. In particular, the scheme is designed to block changes which would put the security of the SPC at risk and only follow IPF set-points within its feasible operational space. By such a control scheme, in future, a TSO could coordinate the behaviour of the SPCs connected to it and by this influence the apparent power balance of single buses of the transmission network. Thus, SPCs could be integrated into the real-time operation of the system and participate e.g. in congestion management and the optimization of the system. The developed control scheme has been tested by means of time-domain simulations using a test system which was developed for this purpose. The simulation results show that the control scheme is able to control the IPF of the test SPC to follow IPF set-points without violating security limits.

C6: A combined transmission-distribution test system has been developed. The test system can be used to design and test control schemes aimed to be implemented in a power system organized according to the SPC concept. The test system has been implemented in Matlab Simulink and can be used to perform time-domain simulations in normal but also contingency situations under consideration of new control schemes. The developed test system is composed of one transmission network, five conventional distribution networks and eight SPCs which are controlled by the scheme described in section 6. In order to demonstrate how the test system can be used to test the impact of cross-voltage-level control schemes on the dynamic behaviour of the entire system, two case studies have been presented. In the first case study, it is shown how the SPCs of the developed test system are coordinated to solve a congestion at the transmission network level. The simulation results show that the power flow of an overloaded transmission line can be reduced by 10 % by coordinating the behaviour of the SPCs.

In the second case study, the impact of a short circuit on the dynamic behaviour of the test system is investigated. In addition, the case study also demonstrates how a voltage problem, which was originated by the short circuit, can be improved by coordinating the behaviour of the SPCs connected to the system.

8.2 Outlook

The architecture and operational concept described in this dissertation do not seek to be a final solution for the challenges associated with the decommissioning of conventional power plants. Instead, they are intended to be a framework aimed at enabling the scientific exchange by providing a common understanding of possible problems and challenges, and suggesting concepts and terms which can be used to design solutions for the efficient, secure and stable operation of future power systems. In this context, considerable research efforts are still required which were not covered in this work. In the following, the main areas of research required for the reorganization of power systems according to the concept described in this dissertation are summarized:

R1: New monitoring, protection and control strategies and schemes for distribution and transmission grids need to be developed, tested and implemented in order to enable the participation of SPCs in the instantaneous operation of the system.

R2: Operational concepts and control schemes need to be designed to integrate SPCs into the real-time operation of the system.

R3: New market frameworks and scheduling procedures under consideration of the new system architecture and increased responsibilities of system users need to be conceived and established such that SPCs can be involved in the operational planning of the system.

R4: The way the power system is planned in the long term must be fully reviewed and modified such that the reliable operation of the system can continue to be guaranteed despite the increasing planning complexity and uncertainty.

R5: The ICT-infrastructure needs to be extended such that monitoring and control entities of the transmission and distribution domain can collect data from measurement devices, send control data to controllable resources and communicate with each other reliably and at sufficient speed.

R6: The way power systems are modelled, simulated and analysed needs to be revised and new methods for the execution of security and stability studies under consideration of the increasing ICT dependency of the system need to be developed.

R7: The current regulation, technical guidelines and network codes need to be revised and adjusted such that involved parties such as manufacturer, utilities, transmission and distribution operators, regulatory entities and academic institutions can start adapting their processes, products and research and development emphasis such that the transformation of the system can be achieved in time.

In addition to these general research targets, following concrete investigations and developments were identified during the elaboration of the dissertation and should be addressed in future work:

D1: In chapter 2, it has been discussed that conventional power plants are essential for the efficient, secure and stable operation of contemporary power systems and that if the number of renewables continues to increase without drastically changing how the system is structured and operated, the system will become non-manageable and the risk of instability will increase. This consequence has been derived in this dissertation based on a logical analysis. However, the validity of this statement needs to be further investigated by means of time-domain simulations. In future work, it could be for instance investigated at what degree of integration of renewable sources the system becomes non-manageable and unstable if the way the system is operated and controlled is not adapted.

D2: In chapter 5, two methods for the estimation of the flexibility of an SPC to support the operation of the transmission network have been described. The computational expensiveness of these methods is very high and thus, estimating the flexibility of SPCs is a very time-consuming procedure. In future, improvements of the methods need to be investigated in order to reduce the required computation times.

D3: In chapter 6, a control scheme for an SPC has been described. However, the scheme focuses on the IPF control of an SPC and not all control objectives defined in section 3.4 are implemented. Thus, the control scheme needs to be extended such that all the identified control objectives are achieved. In particular, grid forming control schemes [4, 8, 18, 69, 92, 101] need to be implemented and the interactions between IPF control and grid forming controls need to be harmonised. Only in this manner, a future power system without conventional power plants can be operated in a stable and secure way.

D4: In chapter 7, the dynamic behaviour of a future power system under consideration of the scheme presented in section 6 has been studied. However, the test system incorporates conventional power plants. In order to investigate the behaviour of a system with 100 % power electronics based generation, simulations without models of conventional power plants need to be conducted. To this, first, grid forming control schemes [4, 8, 18, 69, 92, 101] need to be integrated into the control system of the SPCs. Otherwise, simulations using the developed test system in the absence of conventional power plants can not be conducted. This is intuitive, since a power system without conventional power plants and without grid forming controls is not stable by "nature".

D5: The simulations conducted in chapter 7 are computationally expensive and very time-consuming. In future, if transient stability studies of "real" power systems organized according to the SPC concept need to be conducted, the simulation times can be prohibitive. Thus, it has to be investigated if the behaviour of SPCs including their control structures can be modelled by reduced dynamic equivalents [DM4]. This, however, is a very challenging task, since SPCs can be considered to be hybrid dynamic systems. Due to this fact, the state of the art methods for model order reduction which are used in the power system context can not be directly applied. In this context, the applicability of hybrid system identification methods needs to be investigated.

Bibliography

[1] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH. *Grundsätze für die Ausbauplanung des deutschen Übertragungsnetzes*. Tech. rep. 2018 (cit. on pp. 25, 30).

[2] R. Adhikari and R. K. Agrawal. “An Introductory Study on Time Series Modeling and Forecasting”. In: *Nova York: CoRR* abs/1302.6613 (2013) (cit. on pp. 110–111).

[3] P. Anderson and A. Fouad. *Power System Control and Stability*. Wiley-IEEE Press, New York, 2002 (cit. on p. 10).

[4] C. Arghir, T. Jouini, and F. Dörfler. “Grid-forming control for power converters based on matching of synchronous machines”. In: *Automatica* 95 (2018) (cit. on pp. 51, 61, 172–173).

[5] P. Aristidou, G. Valverde, and T. van Cutsem. “Contribution of Distribution Network Control to Voltage Stability: A Case Study”. In: *IEEE Transactions on Smart Grid* 8.1 (2017), pp. 106–116 (cit. on pp. 2, 32, 127).

[6] J. Barkans and D. Zalostiba. “Blackout Prevention and Power System Self-Restoration”. In: *EUROCON 2007 - The International Conference on "Computer as a Tool"*. 2007, pp. 1547–1554 (cit. on p. 28).

[7] J.-P. Barret, P. Bornard, and B. Meyer. *Power system simulation*. Springer Science & Business Media, 1996 (cit. on p. 79).

[8] H. Bevrani, T. Ise, and Y. Miura. “Virtual synchronous generators: A survey and new perspectives”. In: *International Journal of Electrical Power and Energy Systems* 54 (2014), pp. 244–254 (cit. on pp. 22, 51, 61, 172–173).

[9] F. Capitanescu. “AC OPF-Based Methodology for Exploiting Flexibility Provision at TSO/DSO Interface via OLTC-Controlled Demand Reduction”. In: *2018 Power Systems Computation Conference (PSCC)*. 2018, pp. 1–6 (cit. on pp. 32, 128).

[10] F. Capitanescu. “TSO–DSO interaction: Active distribution network power chart for TSO ancillary services provision”. In: *Electric Power Systems Research* 163 (2018), pp. 226–230 (cit. on p. 33).

[11] L. Chen, H. Y. Li, S. Cox, and K. Bailey. “Ancillary Service for Transmission Systems by Tap Stagger Operation in Distribution Networks”. In: *IEEE Transactions on Power Delivery* 31.4 (2016), pp. 1701–1709 (cit. on pp. 32, 127).

[12] L. Chen, H. Li, V. Turnham, and S. Brooke. “Distribution network supports for reactive power management in transmission systems”. In: *European Energy Market (EEM), 2016 13th International Conference on the* (2014), pp. 1–6 (cit. on pp. 32, 128).

[13] CIGRE Task Force C6-04. “Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources”. In: (2014) (cit. on pp. 118–119, 138–139, 148, 150).

[14] D. A. Contreras and K. Rudion. “Improved Assessment of the Flexibility Range of Distribution Grids Using Linear Optimization”. In: *2018 Power Systems Computation Conference (PSCC)*. 2018, pp. 1–7 (cit. on p. 33).

[15] Deutsche Energie-Agentur GmbH (dena). *dena Ancillary Services Study 2030 - Security and reliability of a power supply with a high percentage of renewable energy*. Deutsche Energie-Agentur GmbH (dena) – German Energy Agency, 2014 (cit. on p. 2).

[16] R D’hulst, J. M. Fernandez, E Rikos, D Kolodziej, K. Heussen, D Geibelk, A Temiz, and C Caerts. “Voltage and frequency control for future power systems: the ELECTRA IRP proposal”. In: *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*. IEEE. 2015, pp. 245–250 (cit. on p. 1).

[17] M. T. Do, A. Bruyere, and B. Francois. “Sensitivity analysis of the CIGRE distribution network benchmark according to the large scale connection of renewable energy generators”. In: *2017 IEEE Manchester PowerTech*. 2017, pp. 1–6 (cit. on pp. 120, 122).

[18] D. Duckwitz. “Power System Inertia”. PhD thesis. 2019 (cit. on pp. 51, 61, 172–173).

[19] O. Elgerd. *Basic electric power engineering*. Addison-Wesley Series in Electrical Engineering. Addison-Wesley Longman, Incorporated, 1977 (cit. on p. 10).

[20] ENTSO-E. *Distributed flexibility and the value of TSO/DSO cooperation*. ENTSO-E, 2017 (cit. on pp. 2, 32).

[21] ENTSO-E. *General Guidelines for reinforcing the Cooperation Between TSOs and DSOs*. ENTSO-E, 2015 (cit. on pp. 2, 32).

[22] ENTSO-E. *Towards smarter grids: Developing TSO and DSO roles and interactions for the benefit of consumers*. ENTSO-E, 2015 (cit. on pp. 2, 32).

[23] ETG Task Force Grundsätzliche Auslegung neuer Netze. *The cellular approach - The basis of successful, cross-regional energy transition*. VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., 2015 (cit. on p. 1).

[24] N. Etherden, M. H. Bollen, and J. Lundkvist. "Quantification of ancillary services from a virtual power plant in an existing subtransmision network". In: *IEEE PES ISGT Europe 2013*. IEEE, 2013, pp. 1–5 (cit. on pp. 32, 128).

[25] European Commission, Directorate-General for Energy. *Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management*. Official Journal of the European Union, L 197, 25. July 2017, 2017 (cit. on pp. 11, 17, 24, 29).

[26] European Commission, Directorate-General for Energy. *Commission Regulation (EU) 2016/1719 of 26 September 2016 establishing a guideline on forward capacity allocation*. Official Journal of the European Union, L 259, 27. September 2017, 2017 (cit. on pp. 11, 24, 29).

[27] European Commission, Directorate-General for Energy. *Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators*. Official Journal of the European Union, L 112, 27. April 2016, 2016 (cit. on pp. 26–28).

[28] European Commission, Directorate-General for Energy. *Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation*. Official Journal of the European Union, L 220, 25. August 2017, 2017 (cit. on pp. 1, 11, 15, 17–19, 23–24, 26, 31).

[29] European Commission, Directorate-General for Energy. *Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing*. Official Journal of the European Union, L 312, 28. November 2017, 2017 (cit. on pp. 11, 24, 29).

[30] European Commission, Directorate-General for Energy. *Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration*. Official Journal of the European Union, L 312, 28. November 2017, 2017 (cit. on pp. 11, 17–18, 23–24).

[31] N. Fonseca, J. Silva, A. Silva, J. Sumaili, L. Seca, R. Bessa, J. Pereira, M. Matos, P. Matos, A. C. Morais, M. Caujolle, and M. Sebastian-Viana. "evolvDSO grid management tools to support TSO-DSO cooperation". In: *CIRED Workshop 2016*. Institution of Engineering and Technology, 2016, 72 (4 .)–72 (4 .) (Cit. on pp. 2, 33).

[32] A. S. Gaur, P. Das, A. Jain, R. Bhakar, and J. Mathur. "Long-term energy system planning considering short-term operational constraints". In: *Energy Strategy Reviews* 26 (2019), p. 100383 (cit. on p. 30).

[33] German Federal Government. *Renewable Energy Sources Act - EEG 2019, German: Erneuerbare-Energien-Gesetz vom 21. Juli 2014 (BGBl. I S. 1066), das zuletzt durch Artikel 5 des Gesetzes vom 13. Mai 2019 (BGBl. I S. 706) geändert worden ist*. BGBl, 2019 (cit. on p. 1).

[34] German Federal Ministry for Economic Affairs and Energy (BMWi). *Final report of the commission for growth, structural change and employment, German: Abschlussbericht der Kommission "Wachstum, Strukturwandel und Beschäftigung"*. Druck- und Verlagshaus Zarbock GmbH und Co. KG, 2019 (cit. on p. 1).

[35] P. Goergens, F. Potratz, M. Godde, and A. Schnettler. "Determination of the potential to provide reactive power from distribution grids to the transmission grid using optimal power flow". In: *2015 50th International Universities Power Engineering Conference (UPEC)*. IEEE, 2015, pp. 1–6 (cit. on p. 33).

[36] G. F. Government. *The Atomic Energy Act - AtG 2018, German: Atomgesetz in der Fassung der Bekanntmachung vom 15. Juli 1985 (BGBl. I S. 1565), das zuletzt durch Artikel 1 des Gesetzes vom 10. Juli 2018 (BGBl. I S. 1122, 1124) geändert worden ist*. BGBl, 2018 (cit. on p. 1).

[37] M. Greve, J. Schwippe, T. Noll, and C. Rehtanz. "Vertical provision of reactive power for voltage stability". In: *Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES*. 2014, pp. 1–6 (cit. on p. 33).

[38] M. Greve, T. Noll, U. Häger, and C. Rehtanz. “Simulation framework for vertical provision of ancillary services”. In: *CIRED Conference 2015*. 2015 (cit. on pp. 32, 128).

[39] L. Grigsby. *Electric Power Generation, Transmission, and Distribution*. Electric Power Engineering Series. CRC Press, 2016 (cit. on p. 11).

[40] G. Grimmett, G. R. Grimmett, D. Stirzaker, et al. *Probability and random processes*. Oxford university press, 2001 (cit. on pp. 110–111).

[41] E. Handschin. *Elektrische Energieübertragungssysteme*. 2nd ed. Heidelberg: Huethig, 1987 (cit. on pp. 10, 65–68, 78).

[42] M. Heleno, R. Soares, J. Sumaili, R. J. Bessa, L. Seca, and M. A. Matos. “Estimation of the flexibility range in the transmission-distribution boundary”. In: *2015 IEEE Eindhoven PowerTech*. IEEE, 2015, pp. 1–6 (cit. on p. 33).

[43] H. Hooshyar, F. Mahmood, L. Vanfretti, and M. Baudette. “Specification, implementation, and hardware-in-the-loop real-time simulation of an active distribution grid”. In: *Sustainable Energy, Grids and Networks* 3 (2015), pp. 36–51 (cit. on p. 138).

[44] IEA-PVPS. *Advanced Cooperation between Distribution and Transmission Network Operation, Summary Report of IEA PVPS Task 14 Activity 2.7 on DSO – TSO cooperation*. IEA-PVPS, 2014 (cit. on pp. 2, 32).

[45] IEEE Committee Report. “Dynamic models for steam and hydro turbines in power system studies”. In: *IEEE transactions on power apparatus and systems* 6 (1973), pp. 1904–1915 (cit. on p. 150).

[46] IEEE Committee Report. “Excitation System Models for Power System Stability Studies”. In: *IEEE Transactions on Power Apparatus and Systems* PAS-100.2 (1981), pp. 494–509 (cit. on p. 150).

[47] IEEE PES-TR22. *Contribution to Bulk System Control and Stability by Distributed Energy Resources connected at Distribution Network*. IEEE, 2017 (cit. on p. 2).

[48] S. Izumi, H. Somekawa, X. Xin, and T. Yamasaki. “Estimation of regions of attraction of power systems by using sum of squares programming”. In: *Electrical Engineering* 100.4 (2018), pp. 2205–2216 (cit. on p. 16).

[49] V. Jalili-Marandi, V. Dinavahi, K. Strunz, J. A. Martinez, and A. Ramirez. "Interfacing Techniques for Transient Stability and Electromagnetic Transient Programs IEEE Task Force on Interfacing Techniques for Simulation Tools". In: *IEEE Transactions on Power Delivery* 24.4 (2009), pp. 2385–2395 (cit. on p. 70).

[50] M. Kraiczy, H. Wang, S. Schmidt, F. Wirtz, and M. Braun. "Reactive power management at the transmission–distribution interface with the support of distributed generators – a grid planning approach". In: *IET Generation, Transmission Distribution* 12.22 (2018), pp. 5949–5955 (cit. on pp. 32, 128).

[51] L. Kristov, P. de Martini, and J. D. Taft. "A Tale of Two Visions: Designing a Decentralized Transactive Electric System". In: *IEEE Power and Energy Magazine* 14.3 (2016), pp. 63–69 (cit. on p. 2).

[52] P. Kundur, N. Balu, and M. Lauby. *Power System Stability and Control.* McGraw-Hill, Inc., 1994 (cit. on pp. 10, 22, 26–27, 78).

[53] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. V. Cutsem, and V. Vittal. "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions". In: *IEEE Transactions on Power Systems* 19.3 (2004), pp. 1387–1401 (cit. on pp. 14, 22).

[54] P. Kundur, N. J. Balu, and M. G. Lauby. *Power system stability and control.* Vol. 7. McGraw-hill New York, 1994 (cit. on pp. 1, 26, 65, 150).

[55] Z. Li, Q. Guo, H. Sun, and J. Wang. "Coordinated Transmission and Distribution AC Optimal Power Flow". In: *IEEE Transactions on Smart Grid* 9.2 (2018), pp. 1228–1240 (cit. on p. 2).

[56] Z. Li, H. Sun, Q. Guo, J. Wang, and G. Liu. "Generalized Master–Slave-Splitting Method and Application to Transmission–Distribution Coordinated Energy Management". In: *IEEE Transactions on Power Systems* 34.6 (2019), pp. 5169–5183 (cit. on p. 2).

[57] C. Liu, F. Chi, X. Jin, Y. Mu, H. Jia, and Y. Qi. "A multi-level control strategy for transmission congestion relief based on the capability from active distribution network". In: *2014 International Conference on Power System Technology*. IEEE, 2014, pp. 2000–2006 (cit. on pp. 32, 127).

[58] P. MacDougall, B. Roossien, C. Warmer, and K. Kok. “Quantifying flexibility for smart grid services”. In: *2013 IEEE Power & Energy Society General Meeting*. IEEE, 2013, pp. 1–5 (cit. on p. 33).

[59] J. Machowski, J. W. Bialek, and J. Bumby. *Power System Dynamics and Stability*. John Wiley & Sons, Ltd, 1998 (cit. on p. 10).

[60] J. Machowski, J. Bialek, and J. Bumby. *Power system dynamics: stability and control*. John Wiley & Sons, 2011 (cit. on pp. 1, 12–14, 22, 26–27, 78–79).

[61] J. Machowski, J. W. Bialek, and J. R. Bumby. *Power System Dynamics - Stability and Control*. 2nd ed. John Wiley & Sons, Ltd, 2008 (cit. on p. 22).

[62] F. Marten, L. Lower, J.-C. Tobermann, and M. Braun. “Optimizing the reactive power balance between a distribution and transmission grid through iteratively updated grid equivalents”. In: *2014 Power Systems Computation Conference*. IEEE, 2014, pp. 1–7 (cit. on pp. 32, 128).

[63] MathWorks. *Simscape Power Systems, R2015b*. Natick, Massachusetts: The Math- Works Inc., 2015 (cit. on pp. 138, 148, 150).

[64] A. von Meier. *Electric Power Systems: A Conceptual Introduction*. Wiley Survival Guides in Engineering and Science. Wiley, 2006 (cit. on pp. 21–22, 25).

[65] F. Milano. *Power System Modelling and Scripting*. London: Springer, 2010 (cit. on pp. 12, 65–69, 78–79).

[66] F. Milano. *Power system modelling and scripting*. Springer Science & Business Media, 2010 (cit. on pp. 13–15, 65, 69).

[67] J. Milanovic, K. Yamashita, S. Martinez Villanueva, S. Djokic, and L. Korunovic. “International Industry Practice on Power System Load Modeling”. In: *IEEE Transactions on Power Systems* 28.3 (2013), pp. 3038–3046 (cit. on p. 70).

[68] F. Muuß, N. G. Hemdan, M. Kurrat, D. Unger, and B. Engel. “Dynamic virtual reactive power plant in active distribution networks”. In: *2015 IEEE Eindhoven PowerTech*. IEEE, 2015, pp. 1–6 (cit. on pp. 32, 128).

[69] B. K. Poolla, D. Groß, and F. Dörfler. “Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response”. In: *IEEE Transactions on Power Systems* 34.4 (2019), pp. 3035–3046 (cit. on pp. 51, 61, 172–173).

[70] K. L. Praprost and K. A. Loparo. “A stability theory for constrained dynamic systems with applications to electric power systems”. In: *IEEE Transactions on Automatic Control* 41.11 (1996), pp. 1605–1617 (cit. on p. 19).

[71] K. L. Praprost and K. A. Loparo. “A stability theory for constrained dynamic systems with applications to electric power systems”. In: *IEEE Transactions on Automatic Control* 41.11 (1996), pp. 1605–1617 (cit. on p. 65).

[72] A. T. Procopiou, K. Petrou, L. F. Ochoa, T. Langstaff, and J. Theunissen. “Adaptive Decentralized Control of Residential Storage in PV-Rich MV–LV Networks”. In: *IEEE Transactions on Power Systems* 34.3 (2019), pp. 2378–2389 (cit. on p. 2).

[73] “Proposed Terms and Definitions for Power System Stability Task Force on Terms amp;amp; Definitions System Dynamic Performance Subcommittee Power System Engineering Committee”. In: *IEEE Power Engineering Review* PER-2.7 (1982), pp. 28–28 (cit. on pp. 12–15).

[74] D. Pudjianto, C. Ramsay, and G. Strbac. “Virtual power plant and system integration of distributed energy resources”. In: *IET Renewable Power Generation* 1.1 (2007), p. 10 (cit. on p. 34).

[75] A. Rabiee, S. M. Mohseni-Bonab, M. Parniani, and I. Kamwa. “Optimal Cost of Voltage Security Control Using Voltage Dependent Load Models in Presence of Demand Response”. In: *IEEE Transactions on Smart Grid* 10.3 (2019), pp. 2383–2395 (cit. on pp. 32, 127).

[76] REN21. *Renewables 2018 global status report*. REN21, 2018 (cit. on p. 30).

[77] A. C. Rueda-Medina, A. Padilha-Feltrin, and J. R. S. Mantovani. “Active power reserve for frequency control provided by distributed generators in distribution networks”. In: *2014 IEEE PES General Meeting | Conference & Exposition*. IEEE, 2014, pp. 1–5 (cit. on pp. 32, 128).

[78] H. Saboori, M. Mohammadi, and R. Taghe. “Virtual Power Plant (VPP), Definition, Concept, Components and Types”. In: *2011 Asia-Pacific Power and Energy Engineering Conference*. 2011, pp. 1–4 (cit. on p. 34).

[79] T. Sadamoto, A. Chakrabortty, T. Ishizaki, and J. Imura. “Dynamic Modeling, Stability, and Control of Power Systems With Distributed Energy Resources: Handling Faults Using Two Control Methods in Tandem”. In: *IEEE Control Systems Magazine* 39.2 (2019), pp. 34–65 (cit. on pp. 65, 68–69, 78–80).

[80] A. Saint-Pierre and P. Mancarella. “Active Distribution System Management: A Dual-Horizon Scheduling Framework for DSO/TSO Interface Under Uncertainty”. In: *IEEE Transactions on Smart Grid* 8.5 (2017), pp. 2186–2197 (cit. on pp. 32, 128).

[81] C. Sandro. “Primary cabin voltage and reactive power control by distributed generators”. In: *2013 IREP Symposium Bulk Power System Dynamics and Control - IX Optimization, Security and Control of Emerging Power Grid (IREP)*. Piscataway, NJ: IEEE, 2013, pp. 1–16 (cit. on pp. 32, 128).

[82] P. Sauer and M. Pai. *Power System Dynamics and Stability*. Prentice Hall, Upper Saddle River, 1998 (cit. on p. 10).

[83] D. A. Sbordone, E. M. Carlini, B. Di Pietra, and M. Devetsikiotis. “The future interaction between virtual aggregator-TSO-DSO to increase DG penetration”. In: *2015 International Conference on Smart Grid and Clean Energy Technologies - ICSGCE 2015*. Piscataway, NJ: IEEE, 2015, pp. 201–205 (cit. on pp. 2, 32, 128).

[84] P. Schäfer, S. Krahl, H. Vennegeerts, and A. Moser. “Analysis of Strategies limiting the Reactive Power Flow between Power Distribution and Transmission Networks”. In: *Proceedings of International ETG Congress 2015*. Piscataway, NJ: IEEE, 2015, pp. 248–254 (cit. on pp. 32, 128).

[85] R. Schwerdfeger and D. Westermann. “Storage management algorithm for schedule based DSO system operation with respect to TSO’s system responsibility”. In: *2014 Power Systems Computation Conference*. IEEE, 2014, pp. 1–7 (cit. on pp. 32, 128).

[86] R. Schwerdfeger, S. Schlegel, D. Westermann, M. Lutter, and M. Junghans. “Methodology for next generation system operation between DSO and DSO”. In: *CIGRE 2016* (2016), pp. 1–9 (cit. on pp. 32, 128).

[87] A. Shokri Gazafroudi, J. M. Corchado, A. Keane, and A. Soroudi. “Decentralised flexibility management for EVs”. In: *IET Renewable Power Generation* 13.6 (2019), pp. 952–960 (cit. on p. 2).

[88] A. Silva, J. Sumaili, J. Silva, L. Carvalho, L. Seca, M. Matos, R. Bessa, G. Schaarschmidt, and R. Hermes. “Assessing DER flexibility in a German distribution network for different scenarios and degrees of controllability”. In: *CIRED Workshop 2016*. Institution of Engineering and Technology, 2016, 201 (4 .)–201 (4 .) (Cit. on p. 33).

[89] T Slot, H Dijk, R Haffner, and A. Welle. “Options for future European Electricity System Operation”. In: *Policy Studies* 2017 (2018), p. 2016 (cit. on pp. 19, 21, 25).

[90] H. Sun, Q. Guo, B. Zhang, Y. Guo, Z. Li, and J. Wang. “Master–Slave-Splitting Based Distributed Global Power Flow Method for Integrated Transmission and Distribution Analysis”. In: *IEEE Transactions on Smart Grid* 6.3 (2015), pp. 1484–1492 (cit. on p. 2).

[91] B. Swaminathan, V. Debusschere, and R. Caire. “Short-term active distribution network operation with convex formulations of power flow”. In: *2017 IEEE Manchester PowerTech* (2017), pp. 1–6 (cit. on p. 2).

[92] A. Tayyebi, F. Dörfler, F. Kupzog, Z. Miletic, and W. Hribernik. “Grid-Forming Converters–Inevitability, Control Strategies and Challenges in Future Grids Application”. In: (2018) (cit. on pp. 51, 61, 172–173).

[93] R. Teodorescu, M. Liserre, and P. Rodriguez. *Grid converters for photovoltaic and wind power systems*. Vol. 29. John Wiley & Sons, 2011 (cit. on p. 79).

[94] G. Valverde and T. van Cutsem. “Control of dispersed generation to regulate distribution and support transmission voltages”. In: *2013 IEEE Grenoble Conference*. IEEE, 2013, pp. 1–6 (cit. on pp. 32, 127).

[95] C. D. Vournas and N. G. Sakellaridis. “Region of attraction in a power system with discrete LTCs”. In: *IEEE Transactions on Circuits and Systems I: Regular Papers* 53.7 (2006), pp. 1610–1618 (cit. on p. 14).

[96] H. Wang, T. Stetz, F. Marten, M. Kraiczy, S. Schmidt, C. Bock, and M. Braun. “Controlled Reactive Power Provision at the Interface of Medium- and High Voltage Level: First Laboratory Experiences for a Bayernwerk Distribution Grid using Real-Time-Hardware-in-the-Loop-Simulation”. In: *Proceedings of International ETG Congress 2015*. Piscataway, NJ: IEEE, 2015, pp. 240–247 (cit. on pp. 2, 32, 128).

[97] A. Weber, T. Beckers, P. Behr, N. Bieschke, S. Fehner, and C. von Hirschhausen. “Longterm Power System Planning in the Context of Changing Policy Objectives–Conceptual Issues and Selected Evidence from Europe”. In: *Studie im Auftrag der Smart Energy for Europe Platform (SEFEP)* (2013) (cit. on p. 11).

[98] H. Yuan and F. Li. “A comparative study of measurement-based Thevenin equivalents identification methods”. In: *2014 North American Power Symposium (NAPS)*. 2014 (cit. on p. 118).

[99] A. Zegers and H. Brunner. “TSO-DSO interaction: An Overview of current interaction between transmission and distribution system operators and an assessment of their cooperation in Smart Grids”. In: *International Smart Grid Action Network (ISAGN) Discussion Paper Annex* 6 (2014) (cit. on pp. 2, 32).

[100] M. Zerva and M. Geidl. “Contribution of active distribution grids to the coordinated voltage control of the swiss transmission system”. In: *2014 Power Systems Computation Conference*. IEEE, 2014, pp. 1–8 (cit. on pp. 2, 32, 127).

[101] Q. Zhong and G. Weiss. “Synchronverters: Inverters That Mimic Synchronous Generators”. In: *IEEE Transactions on Industrial Electronics* 58.4 (2011), pp. 1259–1267 (cit. on pp. 51, 61, 172–173).

[102] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas. “MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education”. In: *IEEE Transactions on Power Systems* 26.1 (2011), pp. 12–19 (cit. on pp. 68, 118, 120, 122).

[103] R. D. Zimmerman, C Murillo-Sanchez, and D. Gan. “MATPOWER user manual, Version 6.0”. In: *School of Electrical Engineering, Cornell University, Ithaca* (2018) (cit. on p. 118).

[104] M. Zipf and D. Most. “Cooperation of TSO and DSO to provide ancillary services”. In: *European Energy Market (EEM), 2016 13th International Conference on the* (2016), pp. 1–6 (cit. on pp. 2, 32, 127).

Publications

[DM1] S. Dalhues, Y. Zhou, O. Pohl, F. Rewald, F. Erlemeyer, D. Schmid, J. Zwartscholten, Z. Hagemann, C. Wagner, D. Mayorga Gonzalez, H. Liu, M. Zhang, J. Liu, C. Rehtanz, Y. Li, and Y. Cao. “Research and practice of flexibility in distribution systems: A review”. In: *CSEE Journal of Power and Energy Systems* 5.3 (2019).

[DM2] F. Dinter and D. Mayorga González. “Operability, reliability and economic benefits of CSP with thermal energy storage: first year of operation of ANDASOL 3”. In: *Energy Procedia* 49.0 (2014) (cit. on p. 9).

[DM3] J. Hinker, T. Wohlfahrt, E. Drewing, S. F. Contreras Paredes, D. Mayorga Gonzalez, and J. Myrzik. “Adaptable energy systems integration by modular, standardized and scalable system architectures: necessities and prospects of any time transition”. In: *Energies* 11.3 (2018), p. 581.

[DM4] H. Hinners, D. Mayorga Gonzalez, and J. Myrzik. “Model Order Reduction of Active Distribution Networks with TSO-DSO Interconnection Power Flow Control”. In: *PowerTech Milano 2019* (2019) (cit. on p. 173).

[DM5] H. Hinners, D. Mayorga Gonzalez, and J. Myrzik. “The Smart Power Cell Concept - A Novel Architecture for a CO2- Neutral, Power-Electronics-Based, Decentralized, Hybrid and Multimodal AC-DC Power System”. In: *ETG-Kongress 2019* (2019) (cit. on pp. 9, 26, 37).

[DM6] H. Hinners, D. Mayorga Gonzalez, J. Myrzik, and C. Rehtanz. “Multivariable control of active distribution networks for TSO-DSO-coordinated operation in wide-area power systems”. In: *at-Automatisierungstechnik* 67.11 (2019).

[DM7] A. Kubis, L. Robitzky, M. Küch, S. C. Müller, B. Jablkowski, H. Georg, N. Dorsch, S. Krey, C. Langesberg, D. Surmann, D. Mayorga, C. Rehtanz, U. Häger, O. Spinczyk, C. Wietfeld, C. Weihs, U. Ligges, J. Myrzik, and J. Götze. “Validation of ICT-Based Protection and Control Applications in Electric Power Systems”. In: *PowerTech, 2015 IEEE Eindhoven*. 2015 (cit. on p. 82).

[DM8] S. Liemann, D. Mayorga Gonzalez, H. Hinners, C. Rehtanz, and J. Myrzik. “Simplified Dynamic Distributed Generator Model for Active Distribution Network Control Design and Modelling”. In: *2020 IEEE*

Power and Energy Society General Meeting (PESGM). 2020 (cit. on pp. 79, 138, 150).

[DM9] D. Mayorga Gonzalez, C. Rehtanz, and J. Myrzik. “The Smart Power Cell Concept: Mastering TSO-DSO Interactions for the Secure and Efficient Operation of Future Power Systems”. In: *IET Generation, Transmission and Distribution* (2020) (cit. on pp. 9, 37, 127–128, 148).

[DM10] D. Mayorga Gonzalez, J. Hachenberger, J. Hinker, F. Rewald, U. Häger, C. Rehtanz, and J. Myrzik. “Determination of the time-dependent flexibility of active distribution networks to control their TSO-DSO interconnection power flow”. In: *2018 Power Systems Computation Conference (PSCC)*. IEEE. 2018 (cit. on pp. 9, 33, 37, 85, 117).

[DM11] D. Mayorga Gonzalez and J. Myrzik. “Probabilistic determination of the operational flexibility of active distribution networks with high penetration of full-converter interfaced renewable distributed generation units”. In: *2015 50th International Universities Power Engineering Conference (UPEC)*. IEEE, 2015 (cit. on pp. 9, 85, 117).

[DM12] D. Mayorga Gonzalez, L. Robitzky, U. Häger, C. Rehtanz, and J. Myrzik. “Dynamic behavior of active distribution networks with DSO-TSO interconnection power flow control”. In: *IREP–2017 Symposium, Espinho, Portugal*. IEEE, 2017 (cit. on pp. 2, 32–33, 37, 127–128, 145).

[DM13] D. Mayorga Gonzalez, L. Robitzky, A. Kubis, J. Myrzik, C. Rehtanz, S. Böcker, and C. Wietfeld. “ICT-Based Integration of Active Distribution Networks in the Monitoring and Control Systems of Future Transmission Networks”. In: *VDE-Kongress 2016 - Internet der Dinge*. Berlin: VDE VERLAG, 2016 (cit. on pp. 9, 37, 53).

[DM14] D. Mayorga Gonzalez, L. Robitzky, S. Liemann, U. Häger, J. Myrzik, and C. Rehtanz. “Distribution network control scheme for power flow regulation at the interconnection point between transmission and distribution system”. In: *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*. IEEE, 2016 (cit. on pp. 32, 127–128, 138, 145, 150).

[DM15] S. C. Müller, V. Liebenau, S. Ruthe, C. Spieker, C. Kittl, S. Dalhues, D. Mayorga Gonzalez, V. Franz, and C. Rehtanz. “The impact of forecasting errors and remedial actions on operational security and efficiency in classical and probabilistic market coupling”. In: *2014 Power Systems Computation Conference*. 2014.

[DM16] B. Nasiri, A. Ahsan, D. Mayorga Gonzalez, C. Wagner, U. Häger, and C. Rehtanz. “Integration of smart grid technologies for voltage regulation in low voltage distribution grids”. In: *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*. 2016.

[DM17] L. Robitzky, D Mayorga Gonzalez, C. Kittl, C. Strunck, J. Zwartscholten, S. C. Müller, U. Häger, J. Myrzik, and C. Rehtanz. “Impact of active distribution networks on voltage stability of electric power systems”. In: *2017 IREP Bulk Power Systems Dynamics and Control Symposium*. 2017.

[DM18] J. Zwartscholten, M. Klaes, D. Mayorga Gonzalez, F. Subhan, A. Narayan, and C. Rehtanz. “Impact of Increased ICT Latency on Active Distribution Network Control”. In: *6th IEEE International Energy Conference (EnergyCon2020)*. 2020.

[DM19] J. Zwartscholten, D. Mayorga Gonzalez, C. Rehtanz, and J. Myrzik. “Hierarchical Distribution Network Control Scheme for Power Flow Regulation at the Interconnection Points between several Voltage Levels”. In: *2018 IEEE 7th International Conference on Power and Energy (PECon)*. 2018 (cit. on pp. 32, 128).

Supervised Master and Bachelor theses

[ST1] A. Ahsan. “Application of Back to Back Converter to Enhance Renewable Distributed Generation Hosting Capacity of the Grid”. ie3-16.122. Master thesis. Technische Universität Dortmund, Sept. 2016 (cit. on p. 79).

[ST2] G. Arguello. “Development of a coordination algorithm to use the flexibility of distributed generating units to provide ancillary services at the coupling point between distribution and transmission network”. ie3-16.030. Master thesis. Technische Universität Dortmund, Apr. 2016 (cit. on pp. 85, 117).

[ST3] M. Baby. “Dynamic Modelling and Analysis of the Active and Reactive Power Control Flexibilities of a Direct Drive wind Energy Converter”. ie3 - 16.043. Master thesis. Technische Universität Dortmund, May 2016 (cit. on p. 79).

[ST4] J. Hachenberger. “Entwicklung einer Methodik zur szenariobasierten Charakterisierung der Flexibilität aktiver Verteilnetze zur spannungsebenenübergreifenden Leistungsflussregelung”. ie3-17.080. Master thesis. Technische Universität Dortmund, Dec. 2017 (cit. on pp. 85, 117).

[ST5] J. Kemper. “Analyse des Blindleistungsverhaltens eines Verteilnetzes unter Berücksichtigung spannungsabhängiger Lastenmodelle und einer koordinierten Wirk- und Blindleistungseinspeisung dezentraler Erzeuger”. ie3-15.100. Bachelor thesis. Technische Universität Dortmund, Oct. 2015 (cit. on p. 85).

[ST6] J. Kemper. “Implementierung eines Optimal Power Flow-Algorithmus zur Zustandsregelung in Aktiven Verteilnetzen”. ie3-17.096. Master thesis. Technische Universität Dortmund, Nov. 2017 (cit. on p. 85).

[ST7] M. Ketteler. “Modellierung und Analyse des dynamischen Verhaltens aktiver Verteilnetze mit spannungsebenenübergreifender Leistungsflusskoordination”. ie3-16.105. Master thesis. Technische Universität Dortmund, Nov. 2016 (cit. on p. 79).

[ST8] J. König. “Analyse und Modellierung der statischen und dynamischen Spannungsabhängigkeit eines exemplarischen Verteilnetzes mit hoher Durchdringung Erneuerbarer Energien”. ie3-17.081. Master thesis. Technische Universität Dortmund, Dec. 2017.

[ST9] M. Meissner. “Modellierung und Analyse der Regelflexibilität von Windenergieanlagen mit doppeltgespeisten Asynchrongeneratoren”. ie3-16.031. Master thesis. Technische Universität Dortmund, Apr. 2016 (cit. on p. 79).

[ST10] C. Nolan. “Dynamische Modellierung und Analyse der Regelflexibilität einer PV-Anlage”. ie3-15.101. Master thesis. Technische Universität Dortmund, Jan. 2016 (cit. on p. 79).

[ST11] C. Rüther. “Untersuchung von U-P-Kurven im Verteilnetz für Last- und Rückspeisefälle”. ie3-15.059. Bachelor thesis. Technische Universität Dortmund, Oct. 2015.

[ST12] C. Strunck. “Konzeptionierung einer zentralen Spannungsregelung im Übertragungsnetz unter Berücksichtigung der Regelflexibilitäten unterlagerter Verteilnetze”. ie3-17.020. Master thesis. Technische Universität Dortmund, Mar. 2017.

[ST13] J. Zwartscholten. “Analyse des dynamischen Verhaltens von elektrischen Energieübertragungsnetzen in spannungskritischen Situationen bei Einbindung aktiver Verteilnetze”. ie3-16.095. Master thesis. Technische Universität Dortmund, Nov. 2016.

List of symbols

Variables and parameters

a	General variable
b	General variable
$\mathbf{c}$	Vector of control signals
$\mathbf{c}^{\mathrm{CPCU}}$	Vector of control signals to control a CPCU
$\mathbf{c}_r^{\mathrm{CPCU}}$	Vector of control signals to control a particular CPCU r
$\mathbf{c}^{\mathrm{DG}}$	Vector of control signals to control a Distributed Generator
C_n^{F}	Discrete state variable which describes the load flow situation of a particular SPC n
$\mathbf{c}^{\mathrm{Fl}}$	Vector of control signals to control a Flexible load
$\mathbf{c}_s^{\mathrm{MACS}}$	Vector of control signals to control a particular monitoring and control system s
C_r^{P}	Discrete state variable which describes if a particular CPCU r has reached its upper or lower active power limit
C^p	Parallel capacitance of a pi-equivalent model of a line or cable
C_r^{Q}	Discrete state variable which describes if a particular CPCU r has reached its upper or lower reactive power limit
$\mathbf{c}^{\mathrm{SPC}}$	Vector of control signals to control a Smart Power Cell (SPC)
$\mathbf{c}_n^{\mathrm{SPC}}$	Vector of control signals to control a particular SPC n
$c^{\mathrm{SPC,mode}}$	Control mode of an SPC
$\mathbf{c}^{\mathrm{St}}$	Vector of control signals to control a storage device
$\mathbf{c}_t^{\mathrm{TS}}$	Vector of control signals to control a particular transmission system t
$\mathbf{c}^{\mathrm{TS}}$	Vector of control signals to control a Transmission System (SPC)
C_n^{V}	Discrete state variable which describes the voltage situation of a particular SPC n
C^X	Input of the block dynamic limiter of the local controller of a CPCU described in chapter 6

D^{err}	Control deviation used as an input of the dynamic limiter of the local controller of a CPCU
$\mathbf{e}$	Vector of external determinants which impact the behaviour of a dynamic system
$\mathbf{E}$	Vector of random processes mapping the stochastic behaviour of the external determinants of a dynamic system
e_e	e-th element of the vector of external determinants $\mathbf{e}$ of a dynamic system
$\mathbf{e}^{\mathrm{CPCU}}$	Vector of external determinants which impact the behaviour of a CPCU
$\mathbf{e}_r^{\mathrm{CPCU}}$	Vector of external determinants which impact the behaviour of a particular CPCU r
$\mathbf{e}^{\mathrm{DG}}$	Vector of external determinants which impact the behaviour of a distributed generator
$\mathbf{e}^{\mathrm{Fl}}$	Vector of external determinants which impact the behaviour of a flexible load
$\mathbf{e}_s^{\mathrm{MACS}}$	Vector of external signals relevant for the dynamic model of a particular monitoring and control system s
$\mathbf{e}^{\mathrm{NPCU}}$	Vector of external determinants which impact the behaviour of a NPCU
$\mathbf{e}_d^{\mathrm{NPCU}}$	Vector of external determinants which impact the behaviour of a particular NPCU d
$\mathbf{e}^{\mathrm{SPC}}$	Vector of external determinants which impact the behaviour of an SPC
$\mathbf{e}_n^{\mathrm{SPC}}$	Vector of external determinants which impact the behaviour of a particular SPC n
$\mathbf{E}_n^{\mathrm{SPC,err}}(\bar{i})$	Random vector to probabilistically describe the forecast errors of the forecasted external determinants which impact the behaviour of a particular SPC n in a future time interval $\bar{i}$
$\mathbf{E}_n^{\mathrm{SPC,dis}}$	Random vector to describe the stochastic behaviour of the external determinants which impact the behaviour of a particular SPC n in a future time interval $\bar{i}$
$\tilde{\mathbf{e}}_n^{\mathrm{SPC}}$	Forecast of the external determinants (influencing factors) which impact the behaviour of a particular SPC n

$\tilde{\mathbf{e}}_{n}^{\mathrm{SPC}}$	Forecast of the external determinants (influencing factors) which impact the behaviour of a particular SPC n for a particular time interval $\bar{i}$
$\tilde{\mathbf{e}}_{n,j}^{\mathrm{SPC}}$	A particular realization j of the random variable $\mathbf{E}_{n}^{\mathrm{SPC,dis}}(\bar{i})$ which probabilistically describes the external determinants (influencing factors) which impact the behaviour of a particular SPC n for a particular future time interval $\bar{i}$
$\mathbf{e}^{\mathrm{St}}$	Vector of external determinants which impact the behaviour of a storage device
$\mathbf{e}^{\mathrm{TS}}$	Vector of external signals which impact the behaviour of a transmission system
$\mathbf{e}_{t}^{\mathrm{TS}}$	Vector of external determinants which impact the behaviour of a particular transmission system t
$\mathbf{h}$	Vector of discrete state variables of a dynamic system
h_s	The s-th element of the vector of discrete states **h** of a dynamic system
$\mathbf{h}_{t}^{\mathrm{TS}}$	Vector of discrete state variables of the dynamic model of a particular transmission system t
$\mathbf{h}^{\mathrm{SPC}}$	Vector of discrete state variables of the dynamic model of an SPC
$\mathbf{h}_{n}^{\mathrm{SPC}}$	Vector of discrete state variables of the dynamic model of a particular SPC n
$\mathbf{h}_{n,q}^{\mathrm{SPC}}$	Randomly generated vector of discrete state variables of a particular SPC n at a random control scenario q
$\mathbf{h}_{s}^{\mathrm{MACS}}$	Vector of discrete state variables of the dynamic model of a particular monitoring and control system s
$\bar{I}$	Complex current
$\bar{i}$	Time interval
$\bar{I}^{\mathrm{CPCU}}$	Complex current injected or absorbed by a CPCU
$\bar{I}^{\mathrm{DG}}$	Complex current injected or absorbed by a distributed generator
$\bar{I}^{\mathrm{Fl}}$	Complex current injected or absorbed by a flexible load
$\bar{I}^{\mathrm{IC}}$	Complex Interconnection Current
$\bar{I}_{i}^{\mathrm{N}}$	Nodal current of node (bus) i
$\mathbf{i}^{\mathrm{N}}$	Vector of nodal current injections
$\bar{I}^{\mathrm{NPCU}}$	Complex current injected or absorbed by a NPCU
$\bar{I}^{\mathrm{PCU}}$	Complex current injected or absorbed by a PCU

$\bar{I}_p^{\mathrm{PCU}}$	Complex current injected or absorbed by a particular PCU p
$\bar{I}^{\mathrm{St}}$	Complex current injected or absorbed by a storage device
k	Current sampling period or time step
$(k-1)$	Previous sampling period or time step
$K_r^{\mathrm{CPCU,P}}$	Constant gain of the active power controller of a particular CPCU r
$K_r^{\mathrm{CPCU,Q}}$	Constant gain of the reactive power controller of a particular CPCU r
$\mathbf{l}^{\max}$	Vector of upper operational limits restricting the operational space of a dynamic system
$\mathbf{l}_r^{\max}$	Vector of upper operational limits restricting the operational space of a dynamic system
$\mathbf{l}^{\min}$	Vector of lower operational limits restricting the operational space of a dynamic system
$\mathbf{l}_r^{\min}$	Vector of lower operational limits restricting the operational space of a CPCU
$\mathbf{m}$	Vector of monitoring signals
m_m	m-th element of the vector of monitoring signals $\mathbf{m}$
$\mathbf{m}^{\mathrm{CPCU}}$	Vector of monitoring signals of a CPCU
$\mathbf{m}_r^{\mathrm{CPCU}}$	Vector of monitoring signals of a particular CPCU r
$\mathbf{m}_d^{\mathrm{CPCU}}$	Vector of monitoring signals of a particular NPCU d
$\mathbf{m}^{\mathrm{E}}$	Vector of monitoring signals of the environment
$\mathbf{m}_s^{\mathrm{MACS}}$	Vector of monitoring signals of a particular monitoring and control system s
$\mathbf{m}^{\mathrm{SPC}}$	Vector of monitoring signals of an SPC
$\mathbf{m}_n^{\mathrm{SPC}}$	Vector of monitoring signals of a particular SPC n
$\mathbf{m}^{\mathrm{TS}}$	Vector of monitoring signals of a transmission network
$\mathbf{m}_t^{\mathrm{TS}}$	Vector of monitoring signals of a particular transmission network t
n_s	Number of discrete states
n_r	Number of CPCUs
n_d	Number of NPCU
n_e	Number of external influencing factors
n_m	Number of monitoring signals
n_c	Number of control signals
n_q	Number of random control scenarios

n_j	Number of iterations to probabilistically determine the IPF-FOR of an SPC
$\mathbf{p}$	Vector describing an operating point within the parameter space of a dynamic System
P	Active power
P_{ij}	Active power flow over a line connecting the buses i and j
$\mathbf{p}_r^{\mathrm{CPCU}}$	Vector describing an operating point within the parameter space of a particular CPCU r
P^{CPCU}	Active power behaviour of a CPCU
P_r^{CPCU}	Active power behaviour of a particular CPCU r
$P_r^{\mathrm{CPCU,ref}}$	Active power reference value (setpoint) of a particular CPCU r
P^{DG}	Active power behaviour of a distributed generator
$P^{\mathrm{DG,max}}$	Maximum active power of a distributed generator
$P^{\mathrm{DG,min}}$	Minimum active power of a distributed generator
P^{Fl}	Active power behaviour of a flexible load
$P^{\mathrm{Fl,max}}$	Maximum active power of a flexible load
$P^{\mathrm{Fl,min}}$	Minimum active power of a flexible load
P^{IPF}	Active Interconnection Power Flow
P_n^{IPF}	Active Interconnection Power Flow of a particular SPC n
$P_n^{\mathrm{IPF,ref}}$	Active Interconnection Power Flow reference value (setpoint) of a particular SPC n
$P_n^{\mathrm{IPF,err}}$	Control deviation of the active Interconnection Power Flow of a particular SPC n
P^{line}	Active power flow over a line
P_l^{loss}	Active power losses over the line l
$\bar{P}_{ij}^{\mathrm{loss}}$	Active power losses of a line or cable connecting the bus i and the bus j
P^{NPCU}	Active power behaviour of a NPCU
$\mathbf{p}_d^{\mathrm{NPCU}}$	Vector describing an operating point within the parameter space of a particular NPCU d
P_d^{NPCU}	Active power behaviour of a particular NPCU d
P^{PCU}	Active power behaviour of a PCU
$\mathbf{p}^{\mathrm{SPC}}$	Vector describing an operating point within the parameter space of an SPC
$\mathbf{p}_n^{\mathrm{SPC}}$	Vector describing an operating point within the parameter space of a particular SPC n

$\mathbf{p}_{n,q}^{\mathrm{SPC}}$	Vector describing a randomly generated operating point within the parameter space of a particular SPC n corresponding to a particular random scenario q
P^{St}	Active power behaviour of a storage device
$P^{\mathrm{St,min}}$	Minimum active power of a storage device
$P^{\mathrm{St,max}}$	Maximum active power of a storage device
$\mathbf{p}^{\mathrm{TS}}$	Vector describing an operating point within the parameter space of a transmission system
Q	Reactive power
Q_{ij}	Reactive power flow over a line connecting the buses i and j
Q^{CPCU}	Reactive power behaviour of a CPCU
Q_r^{CPCU}	Reactive power behaviour of a particular CPCU r
$Q_r^{\mathrm{CPCU,ref}}$	Reactive power reference value (setpoint) of a particular CPCU r
Q^{DG}	Reactive power behaviour of a distributed generator
$Q^{\mathrm{DG,max}}$	Maximum reactive power of a distributed generator
$Q^{\mathrm{DG,min}}$	Minimum reactive power of a distributed generator
Q^{IPF}	Reactive Interconnection Power Flow
Q_n^{IPF}	Reactive Interconnection Power Flow of a particular SPC n
$Q_n^{\mathrm{IPF,ref}}$	Reactive Interconnection Power Flow reference value (setpoint) of a particular SPC n
$Q_n^{\mathrm{IPF,err}}$	Control deviation of the reactive Interconnection Power Flow of a particular SPC n
Q^{line}	Reactive power flow over a line
Q_l^{loss}	Reactive power losses over the line l
$\bar{Q}_{ij}^{\mathrm{loss}}$	Reactive power losses of a line or cable connecting the buses i and j
Q_d^{NPCU}	Reactive power behaviour of a particular NPCU d
Q^{PCU}	Reactive power behaviour of a PCU
$Q^{\mathrm{St,max}}$	Maximum reactive power of a storage device
$Q^{\mathrm{St,min}}$	Minimum reactive power of a storage device
$Q^{\mathrm{St,max}}$	Maximum reactive power of a flexible load
$Q^{\mathrm{St,min}}$	Minimum reactive power of a flexible load
r	Probability of feasibility
r	Reset signal as input for the block resettable integrator with external initial conditions source
$\bar{S}$	Apparent Power

$\bar{S}_{ij}$	Apparent power flow over a line connecting the buses i and j
$\bar{S}^{\mathrm{CPCU}}$	Apparent power behaviour of a CPCU
$\bar{S}_r^{\mathrm{CPCU}}$	Apparent power behaviour of a particular CPCU r
$\bar{S}_r^{\mathrm{CPCU,ref}}$	Apparent power reference value (setpoint) of a particular CPCU r
S^{DG}	Maximum apparent power of a distributed generator
$\bar{S}^{\mathrm{IPF}}$	Apparent Interconnection Power Flow
$\bar{S}_n^{\mathrm{IPF}}$	Apparent Interconnection Power Flow reference value (setpoint) of a particular SPC n
$\bar{S}_n^{\mathrm{IPF,ref}}$	Apparent Interconnection Power Flow reference value (setpoint) of a particular SPC n
$\bar{S}_{n,q}^{\mathrm{IPF}}$	Apparent Interconnection Power Flow of a particular SPC n corresponding to a random control scenario q
$\mathbf{s}^{\mathrm{line,max}}$	Vector of maximum apparent power flows over the lines of an electric grid
$\mathbf{s}^{\mathrm{line,r}}$	Vector of apparent power flows over the lines of an electric grid (receiving end)
$\mathbf{s}_{n,q}^{\mathrm{line,r}}$	Vector of apparent power flows over the lines of a particular SPC n corresponding to a random control scenario q (sending end)
$\mathbf{s}^{\mathrm{line,s}}$	Vector of apparent power flows over the lines of an electric grid (sending end)
$\mathbf{s}_{n,q}^{\mathrm{line,s}}$	Vector of apparent power flows over the lines of a particular SPC n corresponding to a random control scenario q (receiving end)
$\mathbf{s}^{\mathrm{loss}}$	Vector of apparent power losses over the lines of an electric grid
$\bar{S}_{ij}^{\mathrm{loss}}$	Apparent power losses of a line or cable connecting the buses i and j
$\mathbf{s}^{\mathrm{N}}$	Vector of nodal apparent power injections
$\bar{S}_i^{\mathrm{N}}$	Nodal apparent power of bus i
$\bar{S}^{\mathrm{NPCU}}$	Apparent power behaviour of an NPCU
$\bar{S}_d^{\mathrm{NPCU}}$	Apparent power behaviour of a particular NPCU d
$\bar{S}^{\mathrm{PCU}}$	Apparent power behavior of a PCU
$\bar{S}_p^{\mathrm{PCU}}$	Apparent power behavior of a particular PCU p
$\mathbf{s}_n^{\mathrm{SPC}}$	Vector of apparent power flows (sending and receiving ends) over the lines of a particular SPC n
t	time

t^{0}	Start time of a time period
t^{end}	End time of a time period
t_n	n-th time step
t^*	Particular moment in time
T^{Dead}	Delay of communication model
t^{a}	Point in time located in the past
t^{p}	Point in time located in the past
$\mathbf{u}$	Vector of input variables of a dynamic system
$\mathbf{u}$	Vector mapping the active and reactive power behaviour of the PCUs of a power system
$\mathbf{u}_t^{\mathrm{TS}}$	Vector mapping the active and reactive power behaviour of the PCUs of a particular transmission system t
$\mathbf{u}_n^{\mathrm{SPC}}$	Vector mapping the active and reactive power behavior of the PCUs of a particular SPC n
$\mathbf{u}^{\mathrm{CPCU}}$	Vector mapping the active and reactive power behaviour of the controllable PCUs of a power system
$\mathbf{u}_n^{\mathrm{CPCU}}$	Vector mapping the active and reactive power behaviour of the controllable PCUs of a particular SPC n
$\mathbf{u}_{n,q}^{\mathrm{SPC}}$	Randomly generated vector of the active and reactive power behaviour of the controllable PCUs of a particular SPC n at a random control scenario q
$\mathbf{u}^{\mathrm{NPCU}}$	Vector mapping the active and reactive power behaviour of the non-controllable PCUs of a power system
$\mathbf{u}_n^{\mathrm{NPCU}}$	Vector mapping the active and reactive power behaviour of the non-controllable PCUs of a particular SPC n
$\mathbf{u}_{n,j}^{\mathrm{NPCU}}$	Vector mapping the active and reactive power behaviour of the non-controllable PCUs of a particular SPC n associated to a randomly generated scenario j
$\mathbf{u}^{\mathrm{ICT}}$	Vector mapping the input signals which need to be processed by a communication model
$\bar{V}$	Complex voltage
V_i	Voltage amplitude of bus i
$\bar{V}_i$	Complex voltage of bus i
$\bar{V}^{\mathrm{CP}}$	Complex voltage of the connection point (bus) of a PCU
$\bar{V}^{\mathrm{IB}}$	Complex Interconnection Voltage
$V^{\max}$	Upper voltage security limit
$V^{\min}$	Lower voltage security limit
$\bar{V}_i^{\mathrm{N}}$	Complex line-to-neutral voltage of bus i
$\mathbf{v}^{\mathrm{N}}$	Vector of nodal complex voltages (nodal voltage vector)

$\mathbf{v}_{n,q}^{\mathrm{N}}$	Vector of complex nodal voltages of a particular SPC n corresponding to a random control scenario q
$\mathbf{v}^{\mathrm{N,amp,min}}$	Vector of lower voltage amplitude limits of an electric grid
$\mathbf{v}^{\mathrm{N,amp,min}}$	Vector of upper voltage amplitude limits of an electric grid
$\mathbf{v}^{\mathrm{N,SPC}}$	Vector of nodal complex voltages of an SPC
$\bar{V}_i^{\mathrm{p}}$	Complex voltage of the phase p of busbar i
$\bar{V}_i^{\mathrm{SPC}}$	Complex voltage of bus i of an SPC
$\bar{V}_i^{\mathrm{TNB}}$	Complex voltage of bus i of the Transmission network
x	State variable
x	General variable
$\mathbf{x}$	Vector of state variables of a dynamic system
$\hat{x}$	Realization of a random experiment
$\hat{x}(t)$	Realization of a random process
$\dot{\mathbf{x}}$	Vector of time derivatives of state variables of a dynamic system
$\tilde{x}(\bar{i})$	Forecast of the value of x for the time interval $\tilde{\bar{i}}$
$\mathbf{x_0}$	Vector of initial state conditions of a dynamic system
x_0	Input of the resettable integrator with external initial condition source of the local controller of a CPCU
$\hat{x}_w(t)$	One particular possible outcome w (trajectory) of a random process $X(t)$
X	Continuous Random Variable
$X(t)$	Random Process
$\mathbf{X}(t)$	Vector of random processes
$\mathbf{x}^{\mathrm{CPCU}}$	Vector of dynamic state variables of the dynamic model of a CPCU
$\mathbf{x}_r^{\mathrm{CPCU}}$	Vector of dynamic state variables of the dynamic model of a particular CPCU r
$\mathbf{x}^{\mathrm{DG}}$	Vector of dynamic state variables of the dynamic model of a distributed generator
x^{DL}	State of the dynamic limiter of the local controller of a CPCU
x^{err}	Forecast error
X^{err}	Forecast error described as a random variable
$\mathbf{x}^{\mathrm{Fl}}$	Vector of dynamic state variables of the dynamic model of a flexible load

x^{int}	State of the resettable integrator with external initial condition source of the local controller of a CPCU
$\mathbf{x}_s^{\text{MACS}}$	Vector of state variables of the dynamic model of a particular monitoring and control system s
$\mathbf{x}^{\text{NPCU}}$	Vector of dynamic state variables of the dynamic model of a NPCU
$\mathbf{x}_d^{\text{NPCU}}$	Vector of dynamic state variables of the dynamic model of a particular NPCU d
$\mathbf{x}^{\text{St}}$	Vector of dynamic state variables of the dynamic model of a storage device
$x^{\text{St,charge}}$	State of charge of a storage device
$\mathbf{x}_n^{\text{SPC}}$	Vector of dynamic state variables of the dynamic model of a particular SPC n
$\mathbf{x}_t^{\text{TN}}$	Vector of state variables of the dynamic model of a particular transmission system t
$\mathbf{y}$	Vector of algebraic variables of a dynamic system
y	Input of the dynamic limiter of the local controller of a CPCU
y	Input of the dynamic saturation of the local controller of a CPCU
$\bar{Y}_{ij}$	Series admittance of a pi-equivalent model of a line or cable connecting the buses i and j
$\bar{Y}_{i0}$	Parallel admittance of a pi-equivalent model of a line or cable at the side of the bus i
$\hat{\mathbf{y}}$	Vector of additional algebraic variables of a dynamic system
$\mathbf{y}^{\text{DG}}$	Vector of algebraic variables of the dynamic model of a distributed generator
$\mathbf{y}^{\text{Fl}}$	Vector of algebraic variables of the dynamic model of a flexible load
y^{int}	Output of the resettable integrator with external intial condition source of the local controller of a CPCU
$y_r^{\text{int,P}}$	Output of the resettable integrator with external initial condition source of the active power controller of a particular CPCU r
$y_r^{\text{int,Q}}$	Output of the resettable integrator with external initial condition source of the reactive power controller of a particular CPCU r
$\mathbf{y}^{\text{ICT}}$	Vector of signals returned by a communication model

$\mathbf{y}_s^{\mathrm{MACS}}$	Vector of algebraic variables of the dynamic model of a particular monitoring and control system s
y^{max}	Upper limit determined by the dynamic limiter of the local controller of a CPCU
$y_r^{\mathrm{max,P}}$	Upper limit determined by the dynamic limiter of the active power controller of a particular CPCU r
$y_r^{\mathrm{max,Q}}$	Upper limit determined by the block dynamic limiter of the reactive power controller of a particular CPCU r
y^{min}	Lower limit determined by the dynamic limiter of the local controller of a CPCU
$y_r^{\mathrm{min,P}}$	Lower limit determined by the dynamic limiter of the active power controller of a local controller of a particular CPCU r
$y_r^{\mathrm{min,Q}}$	Lower limit determined by the block dynamic limiter of the reactive power controller of a particular CPCU r
$\mathbf{Y}^{\mathrm{N}}$	Admittance matrix
$\mathbf{y}^{\mathrm{PCU}}$	Vector of algebraic variables of the dynamic model of a PCU
y^{sat}	Output of the dynamic saturation of the local controller of a CPCU
$\mathbf{y}_n^{\mathrm{SPC}}$	Vector of algebraic variables of the dynamic model of a particular SPC n
$\mathbf{y}^{\mathrm{St}}$	Vector of algebraic variables of the dynamic model of a storage device
$\mathbf{y}_t^{\mathrm{TS}}$	Vector of algebraic variables of the dynamic model of a particular transmission system t
$\bar{Z}$	Impedance
$\bar{Z}^{\mathrm{L}}$	Series impedance of a pi-equivalent model of a line or cable
$\bar{Z}^{\mathrm{SL}}$	Series impedance of a pi-equivalent model of a line or cable which belongs to an SPC
$\bar{Z}^{\mathrm{TL}}$	Series impedance of a pi-equivalent model of a line or cable which belongs to the transmission network
$\boldsymbol{\eta}$	Vector of controllable parameters of a dynamic system
ϵ	Control deviation integrated by the resettable integrator with external initial condition source of the local controller of a CPCU

Lower indices

c	Control signal
d	NCPCU
e	External influencing factor
i	Busbar, node, bus (start of line)
j	Busbar, node, bus (end of line)
j	Iteration of the method to probabilistically determine the IPF-FOR of an SPC
l	Line
m	Monitoring signal
n	Smart power cell
p	Power conversion unit
q	Random control scenario
r	CPCU
s	Discrete state
s	Monitoring and Control System (MACS)
t	Transmission system
w	Outcome

Sets

$\mathbb{C}$	Set of complex numbers
$\mathcal{D}$	Set of predetermined disturbances a power system is designed to be resilient to
D	Set of NPCUs of a power system
D_n	Set of NPCUs belonging to the SPC n
$\mathcal{D}^{\mathbf{X}}$	Set of probability density functions to describe the stochastic behaviour of a vector of random variables
$\mathcal{D}_n^{\text{SPC,err}}$	Set of probability density functions to describe the stochastic behaviour of the forecast error of the forecasted external determinants of a particular SPC n
$\mathcal{D}_n^{\text{SPC,dist}}(\bar{i})$	Set of probability density functions to describe the stochastic behaviour of the external determinants of a particular SPC n at a future time interval $\bar{i}$
$\mathcal{F}_n^{\text{SPC}}$	Feasible Operation Region (IPF-FOR) of a particular SPC n
$\mathcal{F}_{n,j}^{\text{SPC}}$	Feasible Operation Region (IPF-FOR) of the SPC n corresponding to a particular randomly generated scenario j
$\mathcal{F}_r^{\text{CPCU}}$	Feasible Operation Region (PCU-FOR) of a particular CPCU r
$\mathcal{F}_w^{\text{DSC}}$	Feasible Operation Region (DSC-FOR) of a particular DSC w
$\mathcal{F}^{\text{DG}}$	Feasible Operation Region (FOR) of a distributed generator
$\mathcal{F}^{\text{St}}$	Feasible Operation Region (FOR) of a storage device
$\mathcal{F}^{\text{Fl}}$	Feasible Operation Region (FOR) of a flexible load
$\mathcal{G}$	Set of all existing steady-state stable equilibrium points of a dynamic system
$\mathcal{H}$	Discrete state space of a dynamic system
$\mathcal{K}$	Set of equilibrium points of a dynamic system which are transient stable for a set of predetermined disturbances $\mathcal{D}$
$\mathcal{L}$	Set of equilibrium points of a dynamic system which are transient unstable for a set of predetermined disturbances D
L_n	Set of lines belonging to the SPC n

$\mathcal{M}_{n}^{\mathrm{PCU-FOR}}$	Set of Feasible Operation Regions (PCU-FORs) of the Controllable PCUs which belong to a particular SPC n
$\mathcal{M}_{n,j}^{\mathrm{PCU-FOR}}$	Set of Feasible Operation Regions (PCU-FORs) of the Controllable PCUs which belong to a particular SPC n associated to a randomly generated scenario at the iteration j
$\mathcal{M}_{n}^{\mathrm{DSC-FOR}}$	Set of Feasible Operation Regions (PCU-FORs) of all the Controllable DSCs which belong to a particular SPC n
$\mathcal{M}_{n}^{\mathrm{FOP}}$	Set of random generated operating points of a particular SPC n which do not violate grid constraints
$\mathcal{M}_{n}^{\mathrm{NFOP}}$	Set of random generated operating points of a particular SPC n which violate grid constraints
$\mathcal{P}$	Multidimensional parameter space of a dynamic System
$\mathcal{P}^{\mathrm{SPC}}$	Multidimensional parameter space of the model of an SPC
$\mathcal{P}^{\mathrm{SPC,Feasible}}$	Subset of the multidimensional parameter space P^{SPC} of the model of an SPC in which the SPC can be operated without violating any operational security limit
P_i	Set of PCUs connected to the bus i
Q	Set of random control scenarios
$\mathbb{R}$	Set of real numbers
$\mathbb{R}^n$	Real coordinate space of dimension n
$\mathcal{R}(\mathcal{H})$	Region of attraction of a dynamic system
R	Set of CPCUs of a power system
R_n	Set of CPCUs belonging to the SPC n
$\mathcal{R}_{n,\bar{i}}^{\mathrm{SPC}}$	Scalar field which associates a probability r to each point in the P-Q-plane and describes probability of feseability of IPFs for a particular SPC n at a particular future time interval $\bar{i}$
$\mathcal{S}^{\mathrm{SPC,line}}$	Space of apparent power flows over the lines of an electric grid spanned by the vectors $s^{\mathrm{line,s}}$ and $s^{\mathrm{line,r}}$
$\mathcal{U}$	Power behaviour space of a power system
$\mathcal{V}^{\mathrm{SPC}}$	Space of complex voltages spanned by the complex voltage vector $\mathbf{v}^{\mathrm{N}}$ of an SPC
$\mathcal{V}^{\mathrm{SPC,Feasible}}$	Subset of the space of complex voltages $\mathcal{V}^{\mathrm{SPC}}$ of an SPC in which no voltage limits are violated
W	Set of DSCs of a power system
W_n	Set of DSCs belonging to a particular SPC n
$\mathcal{X}$	Dynamic state space of a dynamic system

$\mathcal{Y}$	Algebraic state space of a dynamic system
Ω	Set of possible Outcomes of a random experiment

Functions and equations

$\boldsymbol{f}$	Set of differential equations
$\boldsymbol{f}_r^{\mathrm{lim,FOR}}$	Set of non-linear functions to describe the restriction of the parameter space of a CPCU r
$\boldsymbol{f}_s^{\mathrm{MACS}}$	Set of differential equations of the dynamic model of a particular monitoring and control system s
$\boldsymbol{f}^{\mathrm{PCU}}$	Set of differential equations of the dynamic model of a PCU
$\boldsymbol{f}^{\mathrm{SPC}}$	Set of differential equations of the dynamic model of an SPC
$\boldsymbol{f}_n^{\mathrm{SPC}}$	Set of differential equations of the dynamic model of a particular SPC n
$\boldsymbol{f}^{\mathrm{TS}}$	Set of differential equations of the dynamic model of a transmission system
$\boldsymbol{f}_t^{\mathrm{TS}}$	Set of differential equations of the dynamic model of a particular transmission system t
f^{X}	Probability density function of the random variable X
f^{Xerr}	Probability density function of the forecast error X^{err}
$\boldsymbol{g}$	Set of algebraic equations
$\hat{\boldsymbol{g}}$	Set of additional algebraic equations of the model of a dynamic system
$\boldsymbol{g}^{\mathrm{PCU}}$	Set of algebraic equations of the dynamic model of a PCU
$\boldsymbol{g}_s^{\mathrm{MACS}}$	Set of algebraic equations of the dynamic model of a particular monitoring and control system s
$\boldsymbol{g}^{\mathbf{res}}$	Set of algebraic equations to describe the restriction of the parameter space of a dynamic system
$\boldsymbol{g}^{\mathrm{SPC}}$	Set of algebraic equations of the dynamic model of an SPC
$\boldsymbol{g}^{\mathrm{SPC}}$	$\boldsymbol{g}_n^{\mathrm{SPC}}$
$\boldsymbol{g}_n^{\mathrm{SPC}}$	Set of algebraic equations of the dynamic model of a particular SPC n
$\boldsymbol{g}^{\mathrm{TS}}$	Set of algebraic equations of the dynamic model of a transmission system
$\boldsymbol{g}_t^{\mathrm{TS}}$	Set of algebraic equations of the dynamic model of a particular transmission system t