BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

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STABILITY ISSUES IN MODERN POWER SYSTEMS

STABILITA V MODERNÍCH ELEKTRICKÝCH SÍTÍCH

DOCTORAL THESIS
DIZERTAČNÍ PRÁCE

AUTHOR AUTOR PRÁCE	Ing. Jan Koudelka
SUPERVISOR ŠKOLITEL	prof. Ing. Petr Toman, Ph.D.

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ABSTRACT

The thesis deals with the issue of stability in modern power systems, which are characterized by an increase in the share of renewable sources and the integration of new technologies. The thesis is conceived as a set of explanatory notes, comments and remarks to peer-reviewed papers published by the author in proceedings and journals. The selected papers presented in the thesis concern three categories: transient (rotor angle) stability of the power system, frequency stability of the power system and under-frequency load shedding. The main topics presented are calculation of critical clearing time as an indicator of transient stability and the possibility of using new technologies, such as charging stations for electric vehicles, to support the system in an emergency state. The fundamental method used for analysis is dynamic simulations on simplified models of power systems.

KEYWORDS

power system stability; transient stability; frequency stability; under-frequency load shedding; dynamic models

ABSTRAKT

Disertační práce se zabývá problematikou stability v moderních elektrizačních soustavách, které jsou typické nárůstem podílu obnovitelných zdrojů a integrací nových technologií. Práce je koncipována jako soubor vysvětlivek, komentářů a poznámek k recenzovaným článkům publikovaným autorem v konferenčních sbornících a časopisech. Vybrané publikace, prezentované v práci, se týkají tří tematických kategorií: dynamická (úhlová) stabilita elektrizační soustavy, frekvenční stabilita elektrizační soustavy a frekvenční odlehčování. Stěžejní prezentovaná témata jsou výpočty kritického času jako ukazatele dynamické stability a možnosti využití nových technologií jako jsou nabíjecí stanice pro elektromobily pro podporu soustavy v nouzovém stavu. Základní používanou metodou analýzy jsou dynamické simulace na zjednodušených modelech soustav.

KLÍČOVÁ SLOVA

stabilita elektrizační soustavy; dynamická stabilita; frekvenční stabilita; frekvenční odlehčování; dynamické modely

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ROZŠÍŘENÝ ABSTRAKT

Disertační práce se zabývá problematikou stability elektrizační soustavy. Stabilita se aktuálně (dle klasifikace z roku 2021) dělí do pěti kategorií, kterými jsou úhlová, napěťová, frekvenční, rezonanční stabilita a stabilita zdrojů připojených k síti přes měnič (výkonovou elektroniku). Ačkoliv spolu jednotlivé katogorie souvisí a spojuje je základní definice stability, problémy řešené v jednotlivých katogoriích, stejně jako používané metody analýzy a modely, se dosti liší. Celkově jde tedy o značně obsáhlé téma a tato práce se věnuje pouze vybraným aspektům této problematiky, konkrétně z oblasti úhlové a frekvenční stability.

Práce je koncipována jako soubor komentářů a poznámek k recenzovaným článkům, které byly autorem publikovány v konferenčních sbornících a časopisech. Odkazy na texty těchto vybraných publikací tvoří přílohu práce.

V části věnované úhlové stabilitě, která se týká schopnosti synchronních generátorů zachovat vzájemné úhly mezi vícero stroji, jsou řešeny vybrané problémy dynamické stability. V prezentovaných publikacích se řeší zejména problematika výpočtu kritického času jako indikátoru dynamické stability, a to z hlediska matematických metod a simulačních výpočtů. Nechybí také problematika posuzování dynamické stability v reálném čase a srovnání různých faktorů, které dynamickou stabilitu ovlivňují, společně s možnostmi jejich zahrnutí do simulačního výpočtu.

Další řešenou problematikou je frekvenční stabilita, která nabývá na významu zejména se snižováním setrvačnosti v soustavě v důsledku odstavování konvenčních zdrojů se synchronními stroji a narůstu počtu rozptýlených nesynchronních zrojů. Tyto změny přináší nutnost hledat nová řešení, která budou poskytovat požadovanou frekvenční odezvu, a to zejména v nouzovém stavu. Prezentované články se zaměřují na využití nových technologií jako jsou nabíjecí stanice pro elektromobily, elektrolyzéry a bateriová úložiště pro podporu frekvence sítě v nouzovém stavu. V prezentovaných případech byly jako poruchy iniciující vznik nouzového stavu použity rozpady synchronního propojení kontinentální Evropy, inspirované skutečnými poruchami z let 2006 a 2021. Do značné míry je v článcích diskutována také problematika sestavování dynamických modelů vhodných pro analýzu frekvenční stability.

Z oblasti frekvenční stability byla speciálně vyčleněna problematika automatického frekvenčního odlehčování jako opatření k zabránění propadu frekvence a vzniku poruchy typu blackout. Rozebrána jsou různá řešení systému frekvenčního odlehčování a jeho nastavení pro správnou odezvu. Dále je komentován příspěvek týkající se porovnání působení frekvenčního odlehčování při systémových a lokálních poruchách podle definovaných algoritmů. V závěru této části jsou představeny současně řešené projekty.

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Author's Declaration

Author:	Jan Koudelka
Author's ID:	164313
Paper type:	Doctoral thesis
Academic year:	2023/24
Topic:	Stability issues in modern power systems

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the paper and listed in the comprehensive bibliography at the end of the paper.

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1 Introduction

The first chapter gives a general overview on the dissertation. It starts with a general background about the modern power systems and motivation for stability assessment. Objectives of the dissertation are then defined. Finally, outline of the dissertation with overview of each chapter is given.

1.1 Background and Motivation

Since the beginning of electrification, power grids are undergoing changes and development. The small local areas sharing a power plant at the turn of the 19th and 20th century were gradually interconnected into local networks; local networks were connected to the regional, and then to the national power systems, until finally, the interconnected networks at the continental level have been established during the 20th century. Power system development resulted into a proven concept of interconnected systems, where the major electricity sources are large power plants (typically heat, gas or nuclear) with high power synchronous units (centralized electricity production). This concept has been progressively optimized, engineers have learnt how to operate and control it. Consumers have got used to reliability of power supply, and electricity has become an indispensable part of human lives.

Nowadays, the well established concept of centralized electricity production based on large power plants ceases to be valid. Power systems are undergoing big changes, which have been made possible mainly by technological development. Let us name some of them:

- decommissioning and phase out of existing power plants, mainly due to technological obsolescence, lack of fuel (decreasing coal mining) or national policies (e.g. nuclear free electricity production),
- increasing penetration of renewable energy sources (RES), e.g. photovoltaics (PVs) or wind plants, and thus the increasing electricity production of these sources,
- increasing electricity consumption and changes in power flows due to RES integration, leading to new problems and challenges in electricity distribution,
- new types of loads such as charging stations for electric vehicles (EVs),
- new and innovated technologies implemented to the grids, such as integration of power electronics in the form of high voltage direct current (HVDC) and flexible alternating current transmission systems (FACTS) devices, advancements in monitoring, protection, control and grid management techniques for planning, real-time operations and maintenance, as well as demand response and energy-efficient load management.

An illustrative summary of changes is in the following Fig. 1.1, taken from [1].

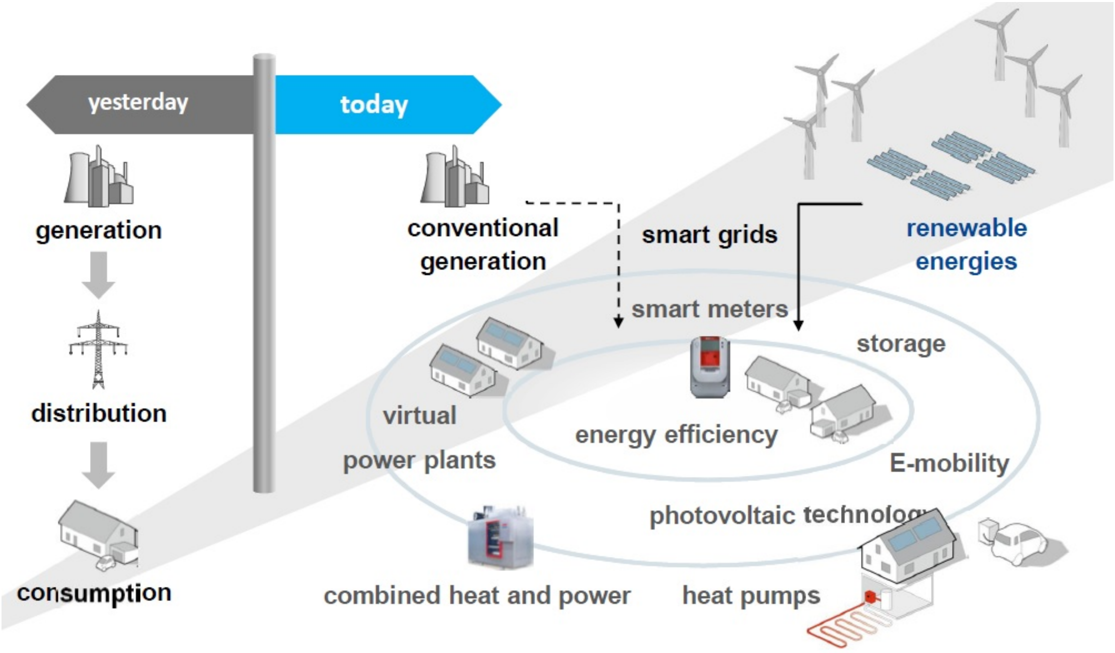


Fig. 1.1: Traditional vs. modern power grid [1]

The aforementioned development and changes of power networks have led to a research of new methods and strategies for grid operation, control, planning, protection and maintenance. All these challenges are in scope of researchers as well as system operators. Proposed or applied methods are published in conference papers and journals, and it is pretty clear that the development is still going on. Even though, many issues are still waiting for their solutions.

One of the areas of interest is also the power system stability, to which has been paid attention from the beginning of interconnected system operation. Power system stability is, in a simplified way, the ability of the system to withstand a disturbance (exact definition follows in the next chapter). Thus, it is of utmost importance for safe and reliable operation of power system. The loss of stable operation can lead to blackout in the worst-case scenario, which has actually happened several times in the past. Blackout is associated with significant economic losses and negative impact on society.

1.2 Objectives of the Dissertation

Power system stability is a very complex topic with a large number of different problems, so it cannot be covered more broadly within one work. Therefore, the thesis focuses on selectively selected issues from the topic and tries to find answers to the following questions.

1. Is it possible to calculate the value of critical clearing time, the indicator of transient stability, in a simplified way? How can its value be availed for on-line stability monitoring?
2. How can the influence on stability of different factors be mathematically modelled? The question concerns both failures and different parts of a synchronous unit. What is their influence?
3. How can simplified dynamic models for frequency stability analysis be built? How to find out their necessary parameters?
4. How to benefit from modern technologies for the purpose of frequency control in an emergency state of the power system? What should be their desired response?
5. What are the applicable algorithms and approaches for under-frequency load shedding? Which problems are they able to solve?

1.3 Dissertation Outline

The dissertation comprises 6 chapters, from which 4 compose the core, and remaining two are introduction and conclusion.

Chapter 2 continues the introduction by bringing the definition and explanation of the subject matter – power system stability. Its classification is explained, together with the related terms, which is needed for understanding the following chapters. Brief summary of history of assessment and selected current problems are also mentioned there.

Afterwards, the three chapters are presenting selected stability issues in the form of comments to published papers (links for the papers themselves can be reached in the appendix). Chapter 3 concerns the issues related to transient stability, chapter 4 is focused on frequency stability. A special issue in the field of frequency stability is the process of automatic under-frequency load shedding, which was detached to the chapter 5.

The last part of the thesis is the chapter 6, concluding about the findings. The appendix of the thesis contains links to full-texts of all eight papers, which are presented and discussed in the thesis.

2 Power System Stability

Stability is one of the most important properties characterizing the behaviour of the dynamic system. This chapter gives the overview of the stability in the context of power systems. It brings the basic definition of the stability types being distinguished, because their clear delimitation is important for the following parts of the thesis. Brief history of stability assessment is presented and the problems currently under investigation are summarized.

It is difficult to arrange these basic parts, because they are interrelated. The definition of the different types of stability and related problems has evolved historically, but it is important to understand the individual terms before talking about them. This was the reason why definitions of stability and its types precede the flashback of their evolution.

2.1 Definition

The fundamental definition of power system stability, which is nowadays used and widely accepted, was brought by the joint Task Force of CIGRE and IEEE committees in 2003 (this work was published in 2003 as a technical brochure and in the IEEE Transactions journal [2] in 2004). According to their report, power system stability can be defined as the ability of the power system to either remain in a state of operating equilibrium under normal operating condition, or to regain a state of equilibrium after being subjected to a disturbance.

The definition is quite general and may refer to various phenomena in the power system. The key point is the equilibrium – the state of balance. In practice, equilibrium is characterized by the invariability of physical quantities (voltages, powers etc.).

2.2 Classification

Stability issues can be split to multiple categories. However, the classification did not use to be unified – and different authors used different classifications. Working with older literature can be challenging in this way, and one should check the definition being used in the specific literature resource. A very meritorious work has been done by the already mentioned CIGRE and IEEE Joint Task Force on Stability Terms and Definitions, proposing also the classification of power system stability. Since then, most of the authors respect the established terminology of rotor angle, frequency and voltage stability (and their subcategories being explained further).

The spread of new technologies being installed to power system required the revision (extension) of the standard [2], which was published 18 years later, in 2021, as [3]. The revision has not changed the original definitions proposed in [2] much; the main change was the addition of two new stability types: resonance stability and converter-driven stability. The diagram of currently distinguished stability types is shown in Fig. 2.1. The basic definitions based on [2] and [3] follows.

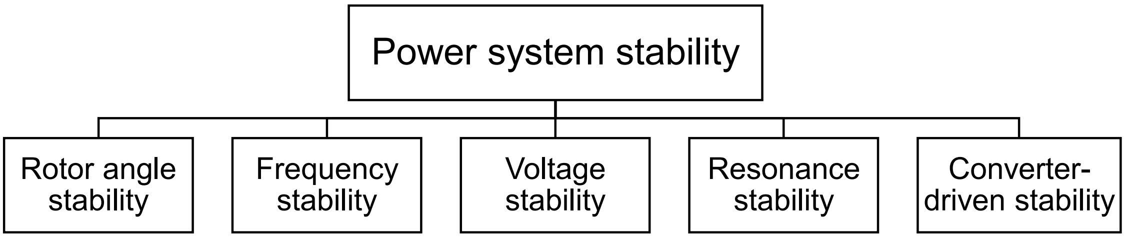


Fig. 2.1: Classification of power systems stability according to [3]

Rotor angle stability

Rotor angle stability is basically the ability of interconnected synchronous machines in power systems to remain in synchronism, under normal operating conditions, and to regain synchronism, after being subjected to the disturbance. The synchronism means keeping the constant difference of rotor angles among the machines. Each machine should keep the equality between the mechanical torque from the prime mover (turbine) and the opposite electromagnetic torque. Rotor angle stability is divided into two sub-categories: **small-disturbance** and **transient** stability. Both small-disturbance and transient stability are short term phenomena, being analysed within the first seconds after disturbance.

Small-disturbance stability is assessed for a small disturbance, e.g. a small change of power flow in the system. It depends on the initial state of the system and can be analysed using linearized model of a power system.

Transient stability is mostly the case of a large disturbances, e.g. switching, outages or faults. The rotor angles are swinging significantly; their evolution is typically examined solving the differential equations using numerical integration methods – they should reach a new equilibrium after disturbance, otherwise, the synchronism and thus stability is lost. Transient stability is determined by the initial operating condition of the power system and also by the severity of the disturbance (e.g. type or location of the fault).

Problems related to the rotor angle stability are discussed in chapter 3.

Frequency stability

Frequency stability is defined as the ability of the power system to maintain the steady frequency after a severe system upset, resulting into the significant unbalance generation/load. The aim is to maintain/restore the equilibrium generation/load with minimum unintentional loss of load. It is worth noting that the key point is the active power balance on the level of the interconnected system.

Upsets resulting into the frequency stability issues can be manifested by significant frequency deviations and large changes of load flow. In large, interconnected power systems, the separation or splitting of the interconnected system to smaller areas may occur – particular parts are then called separates. The frequency stability in this case means that all individual separates are able to reach the operational equilibrium without minimum unintentional loss of load.

Frequency control processes, of which aim is to maintain stability, may have different time duration. The inertial response of synchronous machines within the fractions of seconds is followed by the frequency response of generators, protection tripping and under-frequency load shedding within the duration of seconds, which are considered as a **short-term** phenomena, lasting up to tenths of seconds. **Long-term** phenomena last within minutes and concern the response of prime movers, automatic generation control or manual activation of reserves.

Problems related to the frequency stability are discussed in chapter 4.

Voltage stability

Voltage stability is defined in the same manner as the frequency stability: it is the ability of the power system, for the given initial conditions, to maintain steady voltages at all buses in the power system after the disturbance. It is given by the ability to restore generation/load balance. The key point for voltage stability is the reactive power balance (but active power also plays role).

Voltage instability is mostly related to the load and its response to the disturbance. The most common form of voltage instability is the voltage drop, which may lead to protection tripping causing outages of lines or other components, loss of load or loss of synchronism of some generators.

Voltage stability can be divided into different categories, regarding the disturbance or the time duration. **Large-disturbance** voltage stability is assessed in case of system faults, loss of generation/load and disturbances like that. The stability is strongly influenced by the operation of motors, tap changers on transformers or current limiters of the generators. In comparison, **small-disturbance** is assessed in case of small perturbations such as increase of the load. It is clear that voltage stability involves multiple sub-processes with a different duration. It is useful though to classify the stability in the point of view of time duration. **Short-term** stability is investigated within several seconds, which is the response of devices such as motors, loads or converters. Processes lasting within minutes are the subject of **long-term** stability. Examples of such processes are the change of transformers taps and the action of generators current limiters.

Resonance stability

The category of resonance stability has been introduced in the last revision of the standard [3]. Resonance instability occurs when magnitudes of oscillations exceeds specified limits. Resonance stability can be divided into two sub-categories. **Torsional resonance** is the resonance between the turbine-generator mechanical shaft and series compensated electrical network. **Electrical resonance** is the resonance between converter based generation and series compensated electrical network. It is related mainly to wind power plants with a doubly-fed induction generators.

Converter-driven stability

The last category, introduced also in the last revision of the standard [3], is the converter-driven stability. Its introduction was caused by the increasing spread of converter-interfaced generation, which has implemented fast control loops and algorithms. There can occur the cross-coupling between their fast control algorithms and other dynamics of the network, such as electromagnetic transients in the network or electromechanical transients of machines, leading to power system oscillations over a wide range of frequency. Based on the frequency of oscillations, the converter-driven stability is divided into subcategories fast-interaction and slow-interaction stability.

In case of the **fast-interaction** converter-driven stability, the frequency of oscillations is within the range of 500 Hz – 2 kHz. Such interaction is typical for converter-interfaced generation, HVDC and the response of FACTS devices (e.g. static synchronous compensator – STATCOM). On the other hand, the frequency of oscillations for **slow-interaction** converter-driven stability is typically less than 10 Hz. These oscillations are related mainly to the interaction with devices with a slower response, such as synchronous machines and generator controllers.

2.3 History of Stability Issues

Investigation of the stability of dynamic systems (in general) is a long-standing problem, and the concepts have been researched by many mathematicians, physics and astronomers. Exact definition of stability and the fundamental stability theorems were established by the Russian mathematician Aleksandr Mikhailovich Lyapunov, who published them in the book "The general problem of the stability of motion" in 1892 (English version was published in 1992 [4]).

In that time, at the end of 19th century, the process of electrification was ongoing, and new power systems were being built and, afterwards, interconnected. The stability of the power system has been identified as a serious problem or topic of power system operation soon. Already in the twenties of the 20th century, the first publications dealing with the power system stability started to appear. It was e.g. the paper from Steinmetz [5], related to the operation of the interconnected power systems. First monographs about power system stability were published in 1940s, e.g. the one from Kimbark [6].

In the initial phase, approximately in 1920s–1950s, the stability problems were related mainly to transmission lines (the stability of machines limited the transfer capability of lines). In addition, the stability assessment was limited by the computational capabilities. Development since 1950s have gradually brought analog and digital computers, which made it possible to analyze stability using more accurate calculations and also using dynamic simulations.

The development of computational technologies, but moreover, the development of power systems, in which the trend was the interconnection and parallel operation of larger networks, made other topics come to the fore since 1960s. The faster excitation systems led to the investigation of small-signal rotor angle stability. Disturbances from 1970s and 1980s (blackouts and upsets) led to the increased attention to frequency stability assessment.

Since 1990s, modern computational software is being developed, which is a powerful tool for stability assessment. Development of power systems is also moving forwards. The load is increasing, as well as the number of sources being connected to the networks, environmental constraints have to be considered. All these aspects makes the operation of power system very challenging. Large blackouts from early 2000s proved the need for a careful stability assessment.

The last decade is connected with the increased share of RES (converter-based generation), leading to significant changes in power flows, thus in power system control. In addition, new technologies are also used for power system control, such as FACTS devices. This led to the fact that two new categories of stability associated with resonance and oscillations began to be distinguished.

To conclude, historical evolution clearly shows that there are always new problems and challenges in the field of power system stability. Current problems are presented in the following section.

2.4 Current Problems and Challenges in Stability Assessment

Problems of stability assessment in the past few years revolves around new technologies being installed to the power system. This is clearly manifested by the introduction of two new categories in 2021. New technologies are not only RES, but also e.g. storage systems [7] or HVDC interconnections [8]. Such devices require new dynamic models allowing the stability assessment using dynamic simulations [9].

An increase in consumption is also expected, partly due to the rise of electromobility. On the other hand, managing the process of charging of EVs may bring new functions for grid support, and even for the stability maintenance. The word flexibility is also increasingly used, especially in demand-side management.

Another area is computational procedures. For example, new algorithms based on artificial intelligence are emerging. Advanced modelling platforms are becoming suitable for real-time simulations of grids with a high penetration of RES. This brings new possibilities for real time operation, but also for the stability assessment.

The challenges to stability nowadays are numerous. Selected of them are dealt with in the following chapters of this thesis.

2.5 Summary

Stability assessment is an integral part of the power system operation. It has been investigated since the early operation of power systems, and historical evolution clearly shows that there are always new problems and challenges in this field. A large number of different stability problems are falling into five different categories currently being distinguished: rotor angle, voltage, frequency, resonance and converter-driven stability. Selected stability problems are discussed in the following chapters.

3 Transient Stability

Transient stability is a part of the rotor angle stability. Reminding the definition from [2], it is the ability of the system to maintain in synchronism after a significant disturbance (i.e. the new equilibrium is reached after the disturbance).

The chapter starts with a general introduction to the transient stability assessment. Then, four papers dealing with the issues of transient stability are presented. Specifically, the researched issues are critical clearing time calculation, stability for unbalanced faults, dynamic assessment and the influence of selected factors on transient stability. Introduction to the issue is given before the presentation of the paper itself.

3.1 Methodology of Assessment

Analysis of the dynamic behaviour of the interconnected power system is very challenging. Only the load flow calculation for a large, interconnected power system is problematic due to calculation speed and convergence. If additional differential equations, representing the power system dynamics, are added, the problem may become very complicated or even unsolvable. For that reason, power system analysis steps down to simplified models, making the problem easier and faster to solve. Design of dynamic models requires a lot of expertise. Models should be easy to use, but provide meaningful results.

Going to the models for transient stability studies, the simplest model is the single machine – infinite bus (SMIB) model. SMIB model basically consists of a simple synchronous machine working in parallel with an infinite bus through a couple of parallel tie lines, as shown in the diagram in Fig. 3.1. This model is very simple, but very demonstrative, and its analysis is feasible. The further description and mathematical formulas can be found e.g. in [10]. Transient stability on the SMIB model can be assessed via a very illustrative method of the equal area criterion (EAC), which is based on graphical representation of energies and it is explained also e.g. in [10].

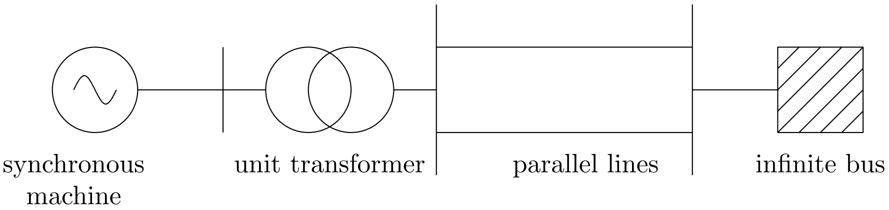


Fig. 3.1: Diagram of a single machine – infinite bus model

SMIB model is widely used in stability assessment for various research purposes. It is applied, for instance, for testing new types of power system stabilizers [11, 12], or the support from different FACTS devices, such as thyristor-controlled series compensation (TCSC) [13], unified power flow controller (UPFC) [14] or STATCOM [15]. It can be used also for stability problems related to the integration of renewable energy sources [16] or the influence of line type [17].

However, the dynamics of interconnected, multi-machine systems are more complex, and the use of only SMIB model is sometimes not sufficient. There are two basic approaches to study the stability of such systems. The first one is to observe the mutual angles of machines, which are the differences between rotor angles of different pairs of machines. The advantage is that we can observe the dynamic response of different machines in a detail; the disadvantage is that the model is complicated due to the consideration of dynamics of multiple machines. This drawback is eliminated in the second approach, called the single machine equivalent (SIME) method. SIME method converts the multi-machine problem to the initially introduced single machine dynamics, used in SMIB model. The approach is described e.g. in [18] or [19]. The transients and stability are assessed against the center of inertia (COI), expressing the average behaviour (motion) of the system. The concept of COI is very suitable for frequency stability assessment, but in terms of rotor angle stability, the informative value of this method may be reduced. The relevant machines must be identified and aggregated to obtain credible waveform as described in [19].

3.2 Swing Equation

Rotor angle stability is strongly related to the dynamics of the synchronous machine. Various models are used for synchronous machines, reflecting both electromagnetic and electromechanical transients. The different models are introduced in [20] or [21]. However, the common way to reflect the electromechanical behaviour is to use the swing equation, which is the equation of the motion and can derived from the balance of torques (turbine and electromagnetic). The swing equation is especially important for frequency stability studies, but it also acts in the transient stability studies.

In its simplest form, the swing equation can be expressed as (3.1), if damping is neglected. Solving the equation (3.1) requires some numerical methods, because it is nonlinear (electrical power on the right side is the function of the angle δ (rad)). Different methods are being proposed for this purpose in the literature [22]. The simplest method is the step-by-step method (also called the method of intervals), but other methods such as Runge-Kutta method are applicable.

$$\frac{T_M \cdot S_n}{\omega_0} \frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = P_0 - P_e \tag{3.1}$$

In (3.1), T_M (s) is the mechanical time constant (it is equal to $2H \rightarrow H$ (s) is the inertia constant), S_n (VA) is the rated apparent power of the machine, ω_0 (rad·s^{-1}) is the synchronous angular speed, P_0 (W) is the mechanical power and P_e (W) is the electrical power. The constant H is more often used in American literature, whereas T_M in European. Its value is important especially for frequency stability, thus it will be discussed more in chapter 4.

3.3 Critical Clearing Time

A typical situation, when the transient stability is assessed, is the fault occurrence. In this case, it is important to find a stability limit, which is given by the critical angle δ_c (rad). Critical angle is the largest value of rotor angle for which the system will remain stable. If we apply the equal area criterion on the SMIB system, this value can be found analytically. However, it is not applicable for practical assessment, as the load angle is not measured. Instead, we would like to know the time when the fault has to be cut off.

The applicable transient stability margin is though the critical clearing time (CCT), which is the maximum fault duration, for which the system remains stable (if the fault is cleared within this time, the machine will remain in synchronism). The value of CCT can be obtained solving the swing equation. It is of importance for proper setting of the protection systems. However, unlike the critical angle, CCT cannot be calculated analytically (in general), as it requires solving the swing equation (3.1) with respect to the rotor angle δ, on which depends also the electrical power P_e.

Therefore, CCT is usually found by the numerical calculation. Conveniently, network simulators can be used for this purpose, which perform calculations on dynamic models and provide the waveforms of different results as the output. Some other methods based on dynamic system theory can be found in the literature, e.g. in [23].

3.4 Paper #1: On Direct Calculation of the Critical Clearing Time

The importance of CCT in stability assessment has been already revealed. The paper is focused on different techniques applicable for direct analytical CCT calculation (without time-domain simulation). The problem of direct CCT analytical calculation is that only approximating formulas can be derived, as the swing equation, generally, cannot be solved analytically. The approximating formulas use the characteristic values of the machine and power transfer, such as the mechanical time constant T_M, machine loading (mechanical power P_0 (W) and corresponding load angle δ_0), transfer capacity during the fault P_{M2} and critical angle δ_c. Two formulas for finding CCT in case of SMIB transfer (Fig. 3.1) were compared. Specifically, these were the equation (3.2), taken from [24], and the equation (3.3), taken from [25]. Equation (3.2) has been derived neglecting the power transfer during the disturbance, whereas the equation (3.3) is based on the averaging the transferred power.

$$t_c = \sqrt{\frac{T_M\left(\delta_c - \delta_0\right)}{\pi f \cdot \dfrac{P_0}{S_n}}} \tag{3.2}$$

$$t_c = \sqrt{\frac{T_M \cdot \left(\delta_c - \delta_0\right)}{\pi f \left(\dfrac{P_0}{S_n} - \dfrac{1}{2}\dfrac{P_{M2}}{S_n} \cdot \left(\sin\delta_0 + \sin\delta_c\right)\right)}} \tag{3.3}$$

The value of CCT is strongly affected by the fault location, which determines the transfer capacity during the fault (3-phase to ground). To cover this aspect, the calculation was done for four different fault locations: at 0 %, 25 %, 50 % and 75 % of the line length. The methodology for assessment of formulas (3.2) and (3.3) was the comparison with time domain simulation in a software tool and also with the numerical, iterative method of swing equation (3.1) solution (step-by-step method). The time domain simulation was used as the reference. Results of comparison are summarized in Tab. 3.1.

Table 3.1: Relative error of CCT compared to the time-domain simulation

	Fault location (% of the line)			
	0	25	50	75
Step-by-step method	12.7	−5.1	−10.0	−21.4
Formula (3.2)	12.7	−21.1	−40.8	−43.6
Formula (3.3)	12.7	2.0	−10.5	−21.4

From the results, it can be concluded that the simplified formulas are suitable for the estimation of CCT, but the difference from the time domain simulations is not negligible. In the worst case, the relative error was more than 43 %. Dynamic model used for the time-domain simulation may be more accurate and better describe the transient phenomena and should be preferentially used if the user is looking for more accurate results. On the other hand, running the time-domain simulation may be computationally intensive, and it requires to enter correctly all parameters. More details about the dynamic model and other results can be found in the paper.

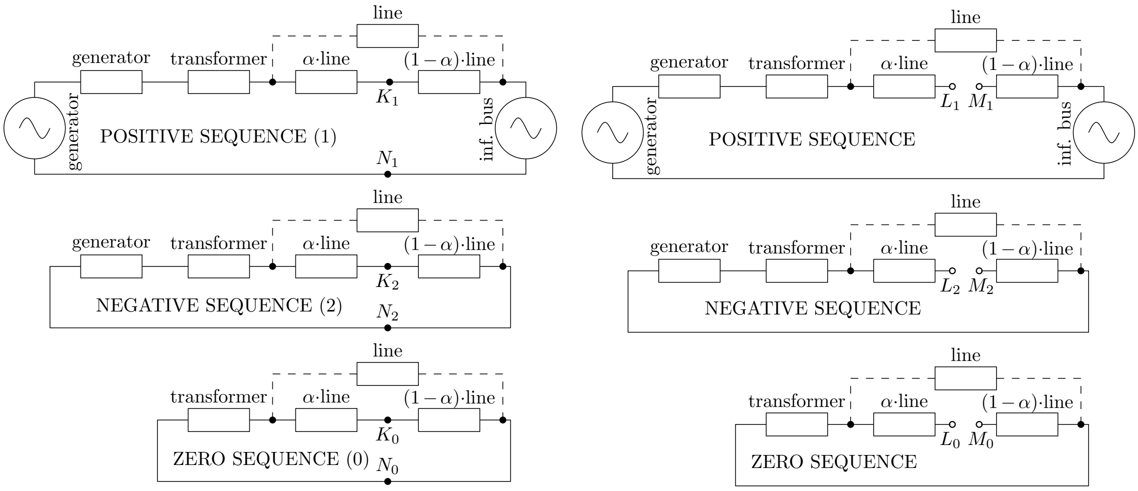
3.5 The Role of Fault Type

Power system is subjected to different types of faults. Faults can be divided into two basic categories, which are shunt and series faults [26]. Shunt faults are short circuits (different types of line-to-line or line-to-neutral connections), whereas series faults are open circuits (one line open and two line open). Except for three-phase short circuit, all these faults are unsymmetrical, which implies the use of corresponding methods for analysis. A common, established method for unsymmetrical power system analysis (and not only the faulted one) is the method of symmetrical components. This method was introduced by Fortescue in 1918, and its gist lies in decomposition of the unsymmetrical power system to the multiple symmetrical components; analysis of these symmetrical components and, at the end, the transformation back to the values of the unsymmetrical system. This method is applicable to multi-phase power systems. However, we will keep the standard three-phase power system, for which there are three corresponding symmetrical components – positive sequence (1), negative sequence (2) and zero sequence (0). For completion, two things should be added. This method is very convenient for a single fault and feasible for two simultaneous faults. Analysing three or more faults using this method is challenging, and in that case, it is better to use phase values of the real system instead of transforming to the symmetrical components. The second thing to add is that the method is well established and preferred (especially for protection systems). However, there do exist other methods based on the decomposition of the unsymmetrical power system such as Clarke method (α, β, 0 components), Kimbark method (S, D, Z components) or Koga method (R, S, T components). These methods do have the application, but they are not usually used for power system analysis.

In power system design, the most commonly used fault is the three-phase short circuit, considered to be the hardest one. It is the general interpretation and it is reasonable, on the other hand, it is not always accurate. The further discussion of this issue is out of scope of this thesis. The effect of different faults can be expressed by their effect on transfer impedance, coupling the machine to the grid. For the SMIB transfer, it can be derived that the transfer impedance (between the machine and the infinite bus) is the lowest in case of a three-phase short circuit, comparing to other types of shunt faults. However, the most common fault in the network is the single-phase-to-ground fault, which is usually being reclosed.

3.6 Paper #2: Transient Stability Assessment for Unbalanced Faults

In this paper, the model for transient stability assessment for unbalanced faults is presented. The model has been derived for the SMIB transfer and it is based on the symmetrical components method. The model has been developed both phases interruption and short circuit faults and it allows to assess different fault location, represented by the coefficient α. Component diagrams are shown in Fig. 3.2 for both shunt and series faults. Terminals K, N or L, M are connected according to Table 3.2, which allows to find the formulas for transfer reactance calculation.



(a) For shunt faults.

(b) For series faults.

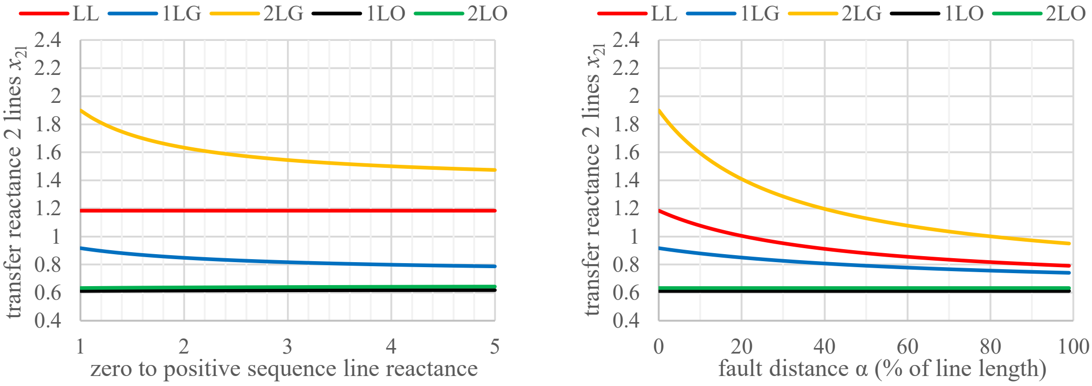
Fig. 3.2: Equivalent component diagram for transient stability assessment

The model allows to perform the sensitivity analysis of different factors affecting the transfer reactance, which was done for multiple cases. The first case was the influence of zero sequence reactance of the line (considered range was from 1 to 5 times the positive sequence reactance) with the fixed fault location of $\alpha = 0$. The most significant effect is in case of two-lines-to-ground fault. The second studied case was the influence of fault location, which was changed from 0 % to 99 % of

Table 3.2: Connection of ports for different types of unbalanced faults

Fault	Shunt faults			Series faults	
	L–L	1L–G	2L–G	1L Open	2L Open
Connected ports	$K_1 - K_2$ $N_1 - N_2$	$K_1 - N_0$, $N_2 - K_0$, $K_2 - N_1$	$K_1 - K_2 - K_0$, $N_1 - N_2 - N_0$	$L_1 - L_2 - L_0$ $M_1 - M_2 - M_0$	$L_1 - M_0$ $L_0 - M_2$, $L_2 - M_1$

the line ($\alpha \in [0; 0{,}99]$). Fault location has no effect on series faults, but can significantly change the transfer reactance in case of two-lines-to-ground fault. Results are presented in Fig. 3.3.



(a) Zero sequence reactance

(b) Fault location

Fig. 3.3: Influence of zero sequence reactance and fault location on the transfer reactance

The last aspect was the line length, but it must be understood in a different way then the previous two factors. In case of line length, the aim is to compare how much each fault worsen the situation for a particular length. It is again the two-line-to-ground fault, for which the increase of transfer reactance is the highest.

To sum up, if we consider the influence of unbalanced faults on the transient stability, measured by the transfer reactance, the most significant has the two-lines-to-ground shunt fault. Analysis of the influence of zero sequence reactance has shown that it is an important factor, thus to get accurate results, it is important to have the correct value of zero sequence impedance. Further description and detailed results can be found in the paper.

3.7 Online Transient Stability Assessment

From the foregoing considerations, it is clear that maintaining the transient stability is important for secure power system operation. All transmission system operators (TSOs) are currently obliged to perform the transient stability studies at least once a year [27]. However, the contemporary development of the grids arises the question whether the assessment performed once a year is sufficient. There is an effort to perform the transient stability assessment more frequently, preferably online. No matter how these ideas may sound logical and reasonable, a question of practical implementation (How should the transient stability assessment be performed?) arise.

A suitable measure for the stability margin is the CCT [28], which can be obtained from dynamic simulation as previously discussed. A three-phase fault is usually considered as the worst fault, leading to the smallest CCT. Using the dynamic model of the power system, dynamic simulation can be used for CCT calculation of a fault in any location. Putting these statements together, one can realize that this way of assessment is time consuming and hardly feasible. Some simplifications needs to be added, if this method should be performed online. These are:

- CCT calculation is done only for faults in selected locations and not for the fault anywhere in the system,
- simplified model of the power system is used for the calculation.

We have already dealt with the issue of power system simplification for transient stability studies. Therefore, let us add a note only to the issue of fault location. From the equations for SMIB transfer [10], it can be revealed that the worst fault is the three-phase short circuit occurring in the substation near a large synchronous unit. These faults pose a considerable risk not only in terms of loss of transient stability, but also in balancing and unit dynamics (the unit cannot supply the power to the system). This is why the TSOs pay considerable attention to them.

3.8 Paper #3: Methods for Dynamic Stability Assessment

The application DSA (abbreviation comes from Dynamic Stability Assessment) has been developed for the purpose of transient stability assessment by the Czech TSO, ČEPS. The basic architecture of the DSA application is schematically shown in Fig. 3.4. It consists of two main parts: the simulation engine DMES and the data preparation module. Data sources and mutual interconnections between individual parts are also depicted in Fig. 3.4.

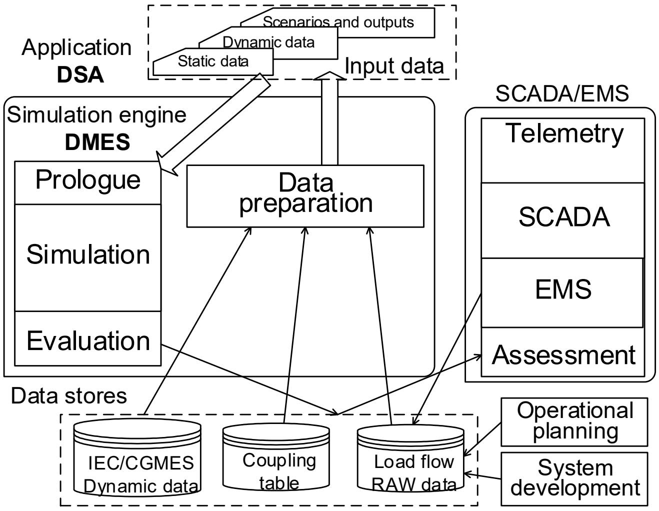


Fig. 3.4: Architecture of the DSA application

The method of stability assessment uses the extended active two-port equivalent, which is the extension of the two-port equivalent published in [29], originally applied for electrical protections design. Equivalent diagram of the two-port equivalent is shown in Fig. 3.5. It consists of two nodes: one near to the disturbance, another far from the disturbance; these nodes are connected together by the faulted line. The model comprises also the directly connected units (close to the fault location). This network equivalent is used for calculation of CCT, its calculation is based on the rotor kinetic energy during the transients. CCT is calculated for the faults close to the units connected to the transmission system. Further explanation of equivalent network creation and CCT calculation method can be found in the paper.

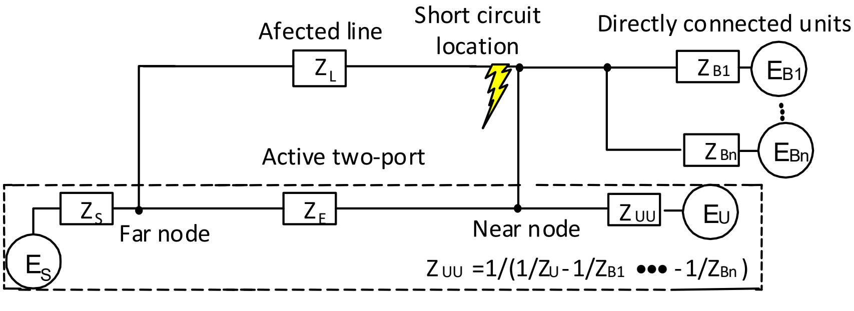


Fig. 3.5: Equivalent diagram of the extended active two-port equivalent

A study has been conducted to validate the proposed method of the active two-port equivalent, using simplified direct methods of transient stability assessment (equal area criterion and direct Lyapunov method). Key findings are that the proposed method is more accurate and more feasible than the use of equal area criterion (SMIB model). It is suitable for the on-line stability assessment. However, the study also revealed the problematic cases. One of them is the operation of synchronous machines in the same substation in two modes – as a generator and as a motor. This can be the case of the pumped-storage power plant (in pumping mode) connected to the same bus as another unit. Simulated case considered 6 generators and 4 units in pumping mode (operating as motors). During the transient, these two groups swing in a different way, which is shown in Fig. 3.6, and it affects the transient stability. Another problematic case is the operation of differently loaded machines in the same bus, which have also different swings. Reliable stability assessment in such cases is done using dynamic simulations.

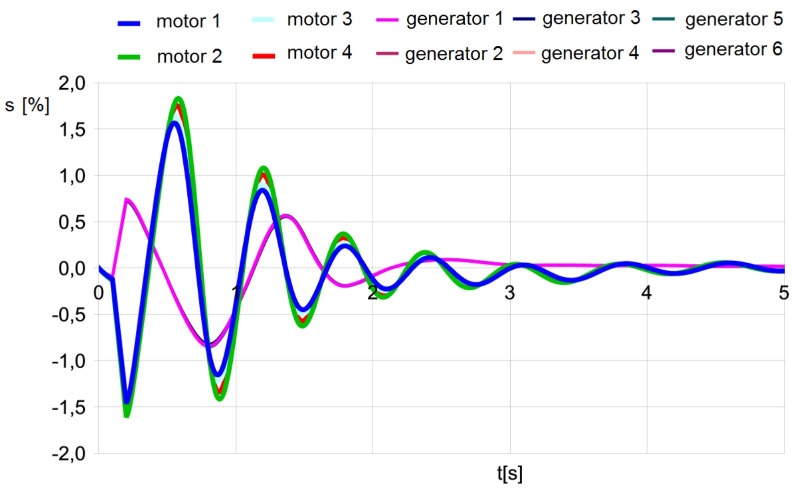


Fig. 3.6: Slip of synchronous machines during the transient

Despite the reservations to the method, the DSA application is used by the Czech TSO for transient stability assessment.

3.9 Factors Affecting Transient Stability

Transient stability can be affected by various factors, which may improve or worsen the situation. These factors can be related either to the machines (machine type, inertia, control), to the load flow (generator dispatch, line impedances, network topology) or to the contingency (fault type, location or duration) [30]. In a real operation of the power system, some factors can be influenced more simply than others (e.g. you can replace some controller, but you cannot modify the machine type). Selected aspects, more related to the machine and controllers, are discussed further. The role of fault type was studied in previous section.

Stability is usually assessed on models (computational or dynamic), which should include these factors in order to get more accurate idea about the actual stability conditions. However, the simulation possibilities are strongly dependent on the models being implemented to the simulation software, and whether it is possible to modify them to fit the modelled devices. Basic facts about the modelling are also discussed in the following text.

Machine type

The basic two types of synchronous machines are round rotor and salient pole synchronous generators. The different construction means different behaviour. The round rotor machines are designed for turboalternators, running at high synchronous speeds (3000 or 1500 r.p.m.). As the inertia depends on the speed, these machines have higher inertia. The second main type is the salient-pole machine, designed for hydrogenerators, running at lower speeds. The inertia is lower, salient-pole machines are more prone to loose of synchronism.

Regarding the mathematical modelling of synchronous machine, the different construction (round rotor vs salient pole) affects the values of reactances in direct and quadrature reactances. It is assumed that for the round-rotor machine these reactances are equal, whereas for salient pole machine are different. To use the salient pole machine in the simulation, the software must allow to use different reactances in direct and quadrature axis. The difference in inertia can be included simply as the machine model must be entered the inertia or mechanical constant. A comprehensive and comprehensible review of synchronous machine modelling can be found in [20].

Excitation system and power system stabilizer

In the simplest computational model, the influence of excitation is neglected – synchronous machine is modelled as a constant voltage behind the reactance. However, the response of the exciter may influence the stability, especially, if the automatic voltage regulator (AVR) acts fast enough. Large interconnected power systems are subjected to the oscillations of low frequencies, which may worsen the stability situation [31]. For damping these oscillations, power system stabilizer (PSS) is connected to AVR. Design and tuning of PSS is challenging.

A very useful standard [32] has been prepared by IEEE. The current version from 2016 is actually the second revision, the first version was published in 1992. The standard comprises the basic models for excitation systems, including different types of exciters, AVRs, PSSs and other controllers. Including dynamic models from this standard in the libraries is a common practice for simulation tools.

Turbine modelling and fast valving

Computational analysis neglects the effect of change of turbine power output. The entire system of turbine and governor has longer response comparing to the time frame of transient stability assessment (turbine modelling is important for frequency stability analysis). It makes sense to include the influence of the turbine only if it is equipped with fast valving. This technique allows to open the valves to quickly decrease the turbine power output, which improves the transient stability.

Turbine modelling is more challenging than modelling of excitation systems, because models are not standardized as in case of excitation systems. There was a significant effort of IEEE, which published the standard [33] in 2013. However, it is still not very widespread, i.e. the models are not included to standard simulation libraries of simulation tools or, if included, they are not named the same. The model of "TGOV3" from this standard may be used for simulation of fast valving.

3.10 Paper #4: Factors Affecting Transient Stability Simulation Possibilities in PSCAD and MODES

The use of dynamic simulations brings the advantage of possible integration of different factors to the stability assessment, which is usually hardly feasible in computational assessment. Such simulations therefore bring more realistic idea about the system behaviour. However, the additional dynamic models require also parametrization and tuning and make the simulation more time and computational demanding.

For application purposes, commercial software tools are applied. It means that users do not build dynamic models from the scratch, but they use the models that are available in the libraries of the software tools. The aim of the paper was to investigate the modelling possibilities of two different simulation tools – PSCAD and MODES, regarding factors affecting the transient stability:

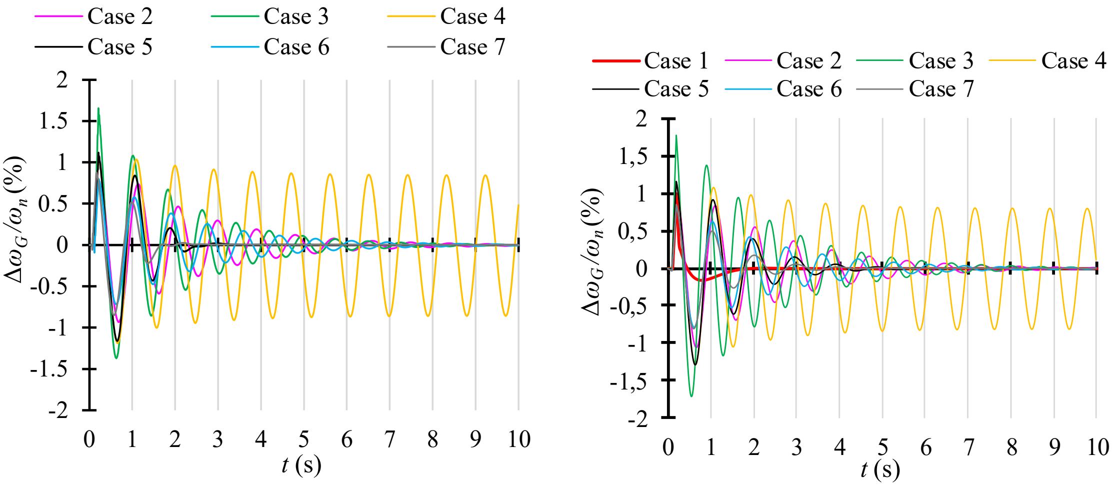
- synchronous machine type,
- AVR,
- fast valving,
- PSS,
- resistance of grid elements.

Speaking in general, both selected tools were designed for power system analysis, but their concept and modelling approach are different. In general, it can be concluded that PSCAD offers more possibilities to users in creation of their own models, but the models need to be properly initialized, which usually requires additional time for simulation. MODES offer less possibilities for users to create their own models. On the other hand, the standard models in libraries are optimized and tuned for direct use in the projects. More detailed discussion and a list of models available in libraries can be found in the paper.

The aim of the paper was also to compare the influence of different aspects on the transient stability, which was done using the selection of 7 simulation cases, specified in Tab. 3.3. Simulations were performed on a simple dynamic model, keeping the same scenario for all cases. Simulations results – slip (speed deviation) of the machine in different cases – are presented in Fig. 3.7. Case 1, with a classical model of synchronous machine, was done only in MODES due to the simulation possibilities of PSCAD (standard PSCAD library does not contain corresponding model).

Table 3.3: Specification of factors included in different test cases

Case	Machine	Exciter	PSS	Resistance
1	Classical model	Constant voltage	NO	NO
2	Park's model – round rotor	Constant voltage	NO	NO
3	Park's model – salient pole	Constant voltage	NO	NO
4	Park's model – round rotor	AVR	NO	NO
5	Park's model – round rotor	AVR	YES	NO
6	Park's model – round rotor	Constant voltage	NO	YES
7	Park's model – round rotor	AVR	YES	YES



(a) PSCAD (b) MODES

Fig. 3.7: Simulation results of different factors influence on the stability

Simulation results match the theoretical assumptions and clearly demonstrate the possibility of simulation tools to include the factors in the simulations. The previous text was focused on the additional factors, leaving out the mathematical modelling of synchronous machine (extensively elaborated e.g. in [20]). The role of machine modelling was demonstrated by the case 1. Further results and discussion can be found in the paper.

The significant finding is that considering these factors in the simulation can improve the stability margin, which is a strong motivation to take them into account and include them in the simulation.

3.11 Summary

The chapter presented four papers related to transient stability. Paper #1 assessed different formulas for CCT calculation. It revealed that the formula (3.3) is suitable for the estimation of CCT. The relative error of the achieved result is compensated by the computational speed compared to the dynamic simulation. Paper #2 gave the methodology to assess the the transient stability in case of unbalanced faults in the power system. These faults have a less adverse effect on stability, but occur more frequently, which may lead to the need for analysis. Paper #3 provided the validation of the method for dynamic stability assessment, which is supposed to be used by the TSO for on-line stability monitoring. The last paper #4 reviewed the simulation possibilities of different factors affecting transient stability in MODES and PSCAD, giving the users a comprehensible summary of models available for their simulations. It also discussed the actual influence of these factors on transient stability.

4 Frequency Stability and Control

Frequency stability is the ability of the power system to maintain steady-state frequency after being subjected to a disturbance. Short-term and long-term frequency stability is being distinguished, as introduced in chapter 2. However, there is no strict border between these two categories. They can be simply understood that the steady-state value of frequency (not necessarily the nominal one) should be reached after disturbance, within tenths of seconds (short-term), and the nominal value of frequency should be reached within the minutes after disturbance (long-term). Maintaining the nominal value of frequency is important for a power system security, as the equipment is designed for this value. It ensures the constant speed of induction and synchronous motors. Also, the electric clocks use the frequency for timing purposes.

This chapter starts with the explanation of individual processes to overcome contingencies in the power system and thus to maintain frequency stability, sorted by the time of their response. The first is the inertial response, the following are frequency control processes. The approach of dynamic simulations for frequency stability assessment is presented afterwards, focusing on the design of appropriate dynamic models. Then, three papers are presented, focusing mainly on stability modelling for the case of power system separation (split), and the possible use of new technologies for providing frequency support in an emergency state.

4.1 Inertial Response

The term of inertia, in physics, is related to the resistance of some object to change in its state motion, which includes also the speed. In context of power system, inertia is related to rotating machines, namely synchronous generators, and it means the resistance to change of their rotational speed. Inertia of a single machine is usually expressed in form of inertia constant H (s), which is the ratio of kinetic energy stored in rotating masses E_{kin} (J) to the rated apparent power of the machine S_n (VA) [34] – see equation (4.1). The value of inertia constant appears in the previously introduced swing equation (3.1), describing the electromechanical transients of the machine.

$$H = \frac{E_{\text{kin}}}{S_n} \tag{4.1}$$

Inertia of the power system is usually calculated as the constant H_{syn} (s), which is based on the parameters of the individual machines (H_i (s), S_{ni} (VA)) connected to the network, as states (4.2). The inertia constant of the power system should reflect both generators and rotating loads.

$$H_{syn} = \frac{\sum\limits_{i=1}^{n} S_{ni} H_i}{\sum\limits_{i=1}^{n} S_{ni}} \tag{4.2}$$

Equation (4.2) is the conventional expression for power system inertia. However, another expression (4.3) has been introduced in [35] to respect the inverter-based generators. The basis in the denominator is changed from the sum of machines' power to the power of load P_{LOAD} (W).

$$H_{syn} = \frac{\sum\limits_{i=1}^{n} S_{ni} H_i}{P_{\mathrm{LOAD}}} \tag{4.3}$$

Inertial response occurs immediately after disturbance, when machines are slowed down (or accelerated) to release the kinetic energy stored in the rotating mass. Lower inertia in the system is manifested by a lower frequency nadir and a faster rate of change of frequency (RoCoF). The phenomena of past years is the inertia reduction, which is caused by the decommissioning of conventional power plants with synchronous machines and their replacement with non-synchronous generation units (RES). This problem has been investigated by many authors and even ENTSO-E conducted several studies (e.g. [35, 36]), concluding that there is no simple or single solution to this problem and all available measures have to be considered and weighted, either in present or in future.

When talking about inertia, one more frequently appearing term should be added, which is the virtual or emulated inertia. Virtual inertia is the combination of RES, energy storage systems, power electronics and a control algorithm, of course, that emulate the inertia of a conventional power system [37]. Despite the main components are still the same, a number of different solutions are distinguished, according to the control algorithm being used [38]. Probably the most known is the virtual synchronous generator (VSG) concept. The use of virtual inertia for the purpose of frequency stability maintenance is currently investigated.

4.2 Frequency Control Processes

Inertial response occurs immediately after the disturbance, but itself, it is not able to stop the fall of frequency. Frequency control processes must be though activated at the same time to restore the active power balance, thus to make the frequency reach a steady value (in short term), and restore the nominal value of frequency (in long term). These processes, formerly known as primary, secondary and tertiary frequency control, are standardized for the European network by the

Commission regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation [27], which came into force in August 2017. This legislation defines basic conditions and requirements for transmission system operation and issues related to power system frequency go obviously through the whole regulation, but the most important part is Part IV: Load-frequency control and reserves. It should be mentioned that it is the role of TSO to ensure the balance, thus to ensure the reserves mentioned below. TSO can ensure them by the own means, or, more often, they are contracted as the ancillary services.

After the occurrence of real power imbalance, the first activated process is a frequency containment process (FCP). The aim of this process is to stabilize the system frequency by activation of the frequency containment reserves (FCR). Frequency containment process is in fact the process commonly (and in the past section) named primary control, the result of this process is a steady-state frequency deviation. The FCR on the level of interconnected grid (Continental Europe – CE) should be dimensioned to cover at least 3000 MW in both positive and negative direction. FCR activation should begin as soon as possible. If frequency deviation exceeds 200 mHz, at least 50 % of full FCR capacity shall be delivered at the latest after 15 seconds and 100 % of full FCR capacity at the latest after 30 seconds. For frequency deviations smaller than 200 mHz, the activated FCR capacity should be proportional with the same time behaviour as for the case when deviation is larger than 200 mHz. Each FCR providing unit shall comply with requirements defined in Annex V of [27].

The following process is the frequency restoration process (FRP). The aim is to restore the frequency back to the nominal value using frequency restoration reserves (FRR). Each TSO should implement an automatic frequency restoration process (aFRP) and manual frequency restoration process (mFRP). The match between commonly used term secondary control and FRP is not straightforward, it can be said that aFRP can be comprehended as the secondary frequency control as its result is restoration of frequency to the nominal value. Sizing of FRR should be based on historical records. FRR is activated in accordance with setpoint from TSO, automatic frequency restoration reserve (aFRR) activation delay should not exceed 30 s. The reserve connecting TSO shall adopt the technical requirements for FRR provider (unit) and FRR provider has to ensure fulfilment of requirements. In case of actual reduction of FRR, provider has to inform TSO as soon as possible.

The second part, mFRP, together with the reserve replacement process (RRP) can be considered as commonly known tertiary frequency control. RRP means activation of replacement reserves (RR) to progressively restore the activated FRR and/or support FRR activation. Reserves have to be able to restore the required amount of FCR and FRR, both positive and negative. Other requirements are similar as for FRR, especially RR should be also activated in accordance with setpoint from TSO and in case of actual reduction, provider has to inform TSO as soon as possible.

The following Fig. 4.1, taken from [39], clearly illustrates previously described processes. At the beginning, there is also noticeable the inertial response.

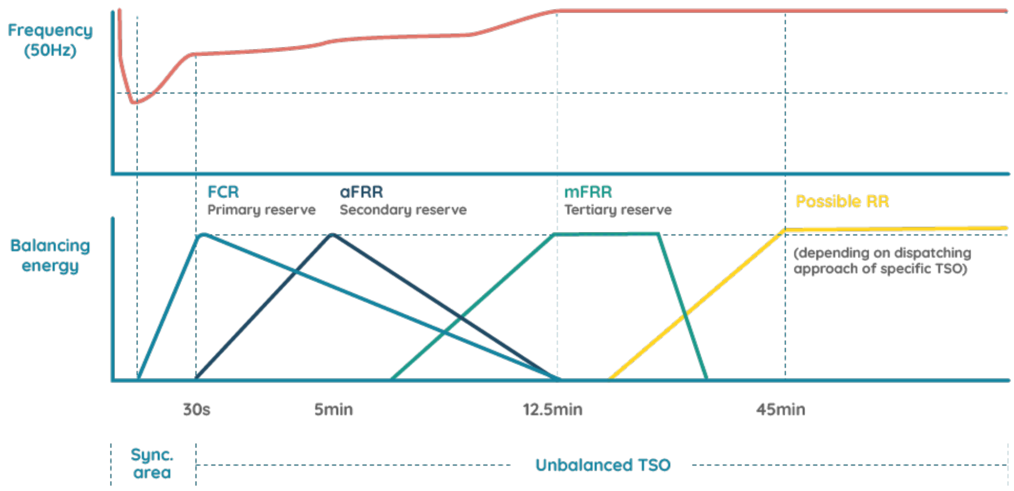


Fig. 4.1: Action of frequency control processes after disturbance [39]

4.3 Dynamic Models for Frequency Stability Studies

Frequency stability is assessed mostly using the dynamic simulations on the simplified models. The fundamental models applicable for frequency studies are briefly introduced, because they are also related to the presented papers.

It should be noted at the beginning that the frequency response is mainly influenced by the dynamics of the primary mover and the response of the machine (electromechanical transient). The main assumption in creation of dynamic models for frequency stability studies is that the dynamic response of the power system depends mostly on the active power imbalance, due to which the frequency deviation occurs. Power sources modify their output based on the frequency deviation, which can be assumed to be similar through the interconnected power system (when inter-area oscillations are neglected). Specific active power flows in the system do not play such an important role, it is sufficient to observe the active power balance on the level of the interconnected power system.

The simplest model for frequency stability studies is a single machine equivalent (SIME), similar to the SMIB model introduced in chapter 3. SIME is a model composed of an equivalent synchronous machine feeding the load, which may or may not be frequency dependent. Using this model, mean frequency in the power system can be obtained, which is a good starting point. Sometimes, this is introduced as the frequency of COI f_{COI} (Hz). Linearized model of SIME can be used even for computational assessment of frequency response without simulations. The description and corresponding formulas are given in [40]. However, this model has limited possibilities, if we want to investigate the frequency support from different types of sources. This disadvantage is eliminated by the following equivalent model.

In the equivalent model, power sources through the system are aggregated to one equivalent unit according to the source type (gas power plants, PVs etc.). The aggregated sources models are connected to a single bus; active power flows in the system are neglected though. Load is also aggregated in the single bus, again, it may or may not be frequency dependent. The model allows to include and investigate dynamic response of different types of power sources (synchronous units, RES, HVDC etc.). The crucial parameters regarding short-term frequency stability are the machine inertia H, rated power (it is a reference for H and the limit for machine operation) and droop characteristic, given mostly by FCR. Other parameters used in dynamic models, such as time constants for electromagnetic phenomena, can be chosen as the typical (realistic) parameters. Usage of the equivalent model for frequency stability studies is quite common. Such type of model has been used e.g. to study behaviour of photovoltaics during solar eclipse [41]; for simulation of the impact of increasing penetration of RES [42] or evaluation of HVDC influence on frequency stability [43].

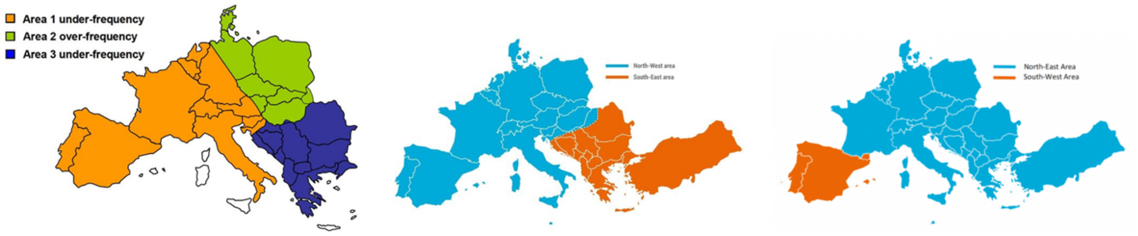
Both previously mentioned types of models use aggregation. On one hand, the parameters of dynamic models can be only estimated, which is advantageous due to the usual unavailability of all relevant data. On the other hand, they do not allow to investigate the interarea oscillations and the frequency in different parts of the system. More detailed models must be used for this purpose, which do respect power flows in the network.

4.4 The Case of Power System Split

Power system split is a special case of a loss of synchronism. The original interconnected power system is split into two or multiple parts, called separates, which remain in synchronism (individually) and try to maintain the frequency stability (stop the fall/rise of frequency due to power imbalance occurring due to separation). Different control processes may be activated in the separates. These are mainly the FCP (but the reserves are split also into different separates), some special protection schemes, disconnecting the loads, help via HVDC links or other means with frequency response, up to the under-frequency load shedding as a last possibility to avoid the blackout occurrence.

Occurrence of the power system split is difficult to predict, and it is even more difficult to predict the actual location of the separation line. The clue could be the significant power flow through a weakened profile. In that situation, if one line is tripped, there is a threat of overloading of other lines in the profile, causing also the tripping etc. This is called the cascading effect.

European power system (CE) has already suffered from several splits. Probably the most known occurred in 2006, when the CE synchronous area was split into 3 islands (separates) as shown in Fig. 4.2 a. Other two incidents happened in 2021. In January, the synchronous area was split in half. There was also the separation of Iberian Peninsula in July of the same year. Separated parts are indicated in Fig. 4.2 b, c. The following papers being presented refer to the incidents from 2021.



(a) 2006 [44]

(b) January 2021 [45]

(c) July 2021 [46]

Fig. 4.2: Different splits of the Continental Europe synchronous area in history

4.5 Paper #5: Simplified Dynamic Model for Continental Europe Synchronous Area Separation

The problematic part of the design of dynamic models is the data acquisition, because data are often confidential, available on request (when it is highly uncertain that the request will be granted) or not available at all. Researchers willing to build such models have to somehow overcome the obstacle of data acquisition. The possible way is to use reports and studies published by ENTSO-E, TSOs, distribution system operators (DSOs) or other authorities. Good data source are platforms for data share (e.g. Transparency Platform [47]) and network development plans. However, if exact data are not available, there is no choice but to use an estimate based on experience or use typical values.

In addition, complex power system modelling usually requires a certain level of simplification to make the simulation less computational-demanding. Engineering practice and experience is though required to prepare a dynamic model, which is feasible to build and run and which provides credible results at the same time.

The paper presents the model which has been used for the simulation of the incident from January 2021 (Fig. 4.2 b), together with relevant data sources which have been used for its creation. The diagram of the model is shown in Fig. 4.3, from which is evident that the model is in form of SIME. The dynamics of the power systems is mainly given by the main machines (G1 and G2) dynamics, other sources shown in Fig. 4.3 are modelled only as a power injection and they were added to the model only to replicate the scenario of the real incident. More information about the parameters of the model and scenario can be found in the paper.

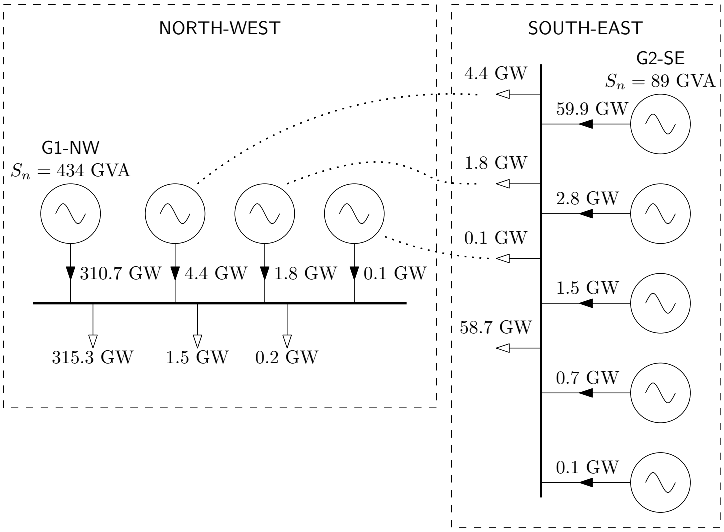
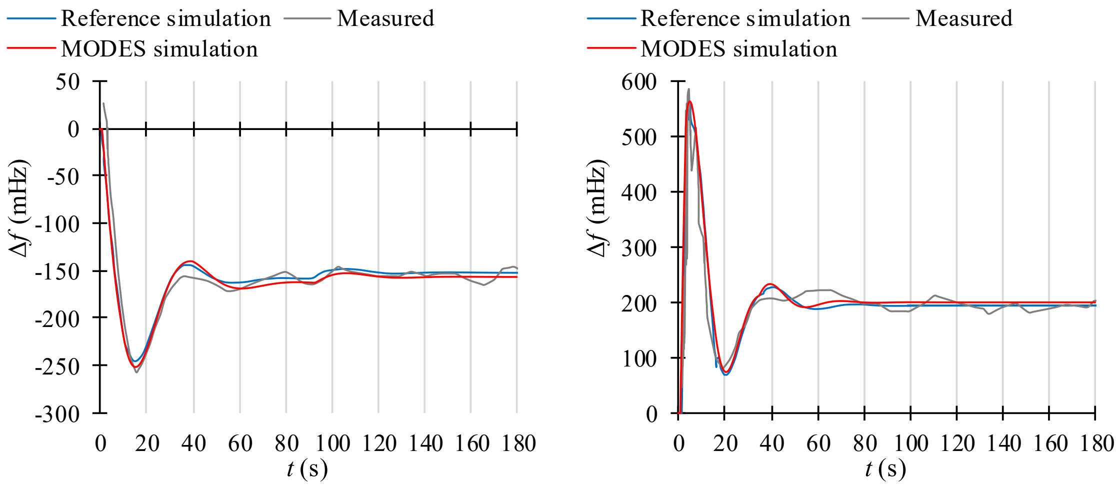


Fig. 4.3: Single line diagram of the dynamic model

The model has been validated against the measured values and simulation results published in [48]. All waveforms are shown altogether in Fig. 4.4. It is clear that results are pretty matching. The compliance has been reached by scenario modification. There is a steady-state frequency deviation as only the short-term frequency stability is simulated (inertia response and FCP) and not further processes (FRP and RRP).

Based on the results, it can be summarized that the simplified dynamic model for frequency stability studies can be built based on publicly available data. The dynamic simulation gives the credible response for the system frequency. However, one should keep in mind that the presented modelling approach has limitations; e.g. it is impossible to replicate the interarea oscillations, or dynamics of different types of sources cannot be assessed. These limitations were the motivation for building more advanced models, which were used for analysis and simulations presented in following sections.



(a) North-West

(b) South-East

Fig. 4.4: Simulation results from the SIME model

4.6 Use of New Technologies for Frequency Support

Technological development over last decades brings new materials, technologies and possibilities in the field of electrical engineering, and power systems are not left behind. This can be seen especially in the field of power electronics. Devices based on power electronics bring new possibilities for grid support, mainly because of their fast response. They are able to solve the problems of power flows, voltage dips or frequency support. It is not just about FACTS devices, but other controllable devices such as battery storage or charging stations for electric vehicles seem to be able to provide grid support.

The search for an energy storage is up to date because of increasing share of renewable sources with intermittent and varying production. Building a large number of pumped storage plants, conventionally used for storing energy, is not feasible. Thus, there are emerging solutions such as battery energy storage systems (BESS) or gas production by electrolysis (power-to-gas – P2G).

BESS are converter-interfaced group of batteries, connected to the power system. Suitable inverter control algorithm allows to provide the desired response. BESS have been used for various applications and others are researched. They are often used in microgrids in islanded operation with a high share of RES [49]. BESS have also shown the potential for ancillary services provision (provision of frequency control reserves) [50], which can be either FCR (former primary control) [51, 52], or RR [53].

P2G is a solution which uses the excess electricity to produce some kind of gas using electrolyser. There can be different gases produced, but the most often the gases are hydrogen and methane [54]. Electrolysis requires direct current supply, thus the electrolyser is converter-interfaced for connection to the standard, AC system [55]. Electrolysers have fast response and high flexibility, which allows flexible response to the current state of the network (especially the production of RES [56]). There have been proposed also their use for ancillary services provision [57].

Converter-interfaced are also **HVDC interconnections**, which are primarily used to connect different synchronous areas unable to work in parallel. Other frequent application is the connection of offshore wind farms. However, HVDC links may be used also inside the synchronous area. Speaking of European power system, there do exist tens of HVDC interconnections (of all types) [58], and others are planned or under construction. Interconnections between different synchronous areas may be used for providing frequency support. It is recommended to implement the Limited frequency sensitivity mode (LFSM) control, which allows to increase the transferred power to the deficient power system in case of under-frequency [59]. LFSM has a smooth behavior (the increase of power is proportional to the frequency deviation), whereas the Emergency power control (EPC) is usually a step response (step change for a defined frequency threshold) [60].

Previously summarized solutions were designated mainly for a grid support in a normal state, mainly for provision of ancillary services. However, the converter control allows to provide the response also in emergency state, which occurs when frequency deviates out of the range of 50 ± 0.2 Hz. Following two papers deal with this issue, taking into account also the potential support from **EVs charging stations**.

4.7 Paper #6: Grid Frequency Support from Electric Vehicle Charging Stations

The share of EVs is increasing worldwide nowadays, and this trend will continue in the future. Some countries have already set ambitious goals to have 100 % of EV share in the future [61]. The increasing number of EVs implies the need of integration of charging stations to the power system, which brings both pros and cons. On one hand, charging stations have big installed capacities (comparing to households) and obviously the electricity demand grows; they increase the presence of power electronics in the power system with very fast response. On the other hand, they can be used for grid support to solve the power quality issues (harmonics, voltage issues), used as a short-term storage or provide the frequency support, even the black start support [62]. It is important to state that EV chargers do not directly contribute to the grid support by themselves, all the mentioned functions can be reached by the additional controllers. Grid support functions still requires standardization and incentives from DSOs, and also the coordination and communication is needed for the implementation. Grid support from electric vehicles (V2G – vehicle to grid) is currently not implemented, and it is neither required by legislation. V2G is currently realized only on the level of laboratory testing and pilot projects.

Focusing on the grid frequency support in emergency state (when frequency drops below 49.8 Hz), EV chargers may decrease their consumption and, in addition, discharge the batteries in vehicles being connected, which serve as the short-term storage. Four different strategies (modes) of frequency support have been tested:

- **no support**, when the charging of EVs continues with the constant power despite the frequency deviation;
- **step change**, when the charging of EVs is stopped when frequency reaches the threshold of 49.8 Hz;
- **LSFM mode**, when the charging of EVs is decreased with a defined droop, in our case 5 %;
- **step change + LFSM**, combining the previous two modes: when the charging of EVs is stopped when frequency reaches the threshold of 49.8 Hz and, in addition, the batteries are being discharged with a defined droop, in our case 5 %.

All four strategies are shown in Fig. 4.5. The negative value of power means charging, while the positive value of power means discharging.

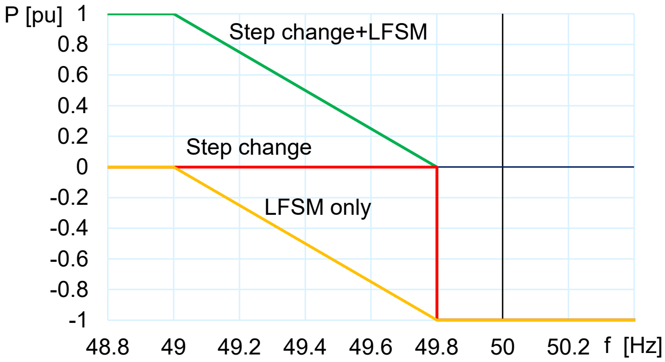


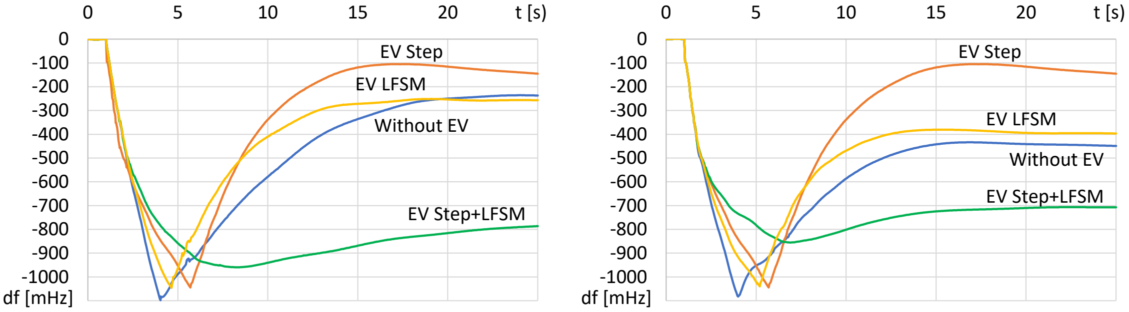
Fig. 4.5: Different frequency responses of EVs charging stations used in the model

A dynamic model was used to test the different control strategies of EV chargers and their contribution. The model consists of 20 nodes representing control areas in the power system of CE, and it was parameterized according to the source base estimates for 2030 (data were taken from ERAA – European Resource Adequacy Assessment database). The advantage of such a model is that it allows to create different splits of the power system, which were chosen as the contingencies and the cause of emergency state occurrence. More details about the model can be found in the paper.

Two system splits were considered as simulation scenarios:

1. Separation of control areas of Spain and Portugal, which was inspired by the real incident from 2021 and there was a risk of under-frequency load shedding (UFLS) activation in the separated part. The installed capacity was 1522 MW. It was considered that charging stations are loaded to half of their capacity and all connected EVs are capable to provide the desired frequency support. The power unbalance of the separated island was −2834 MW.
2. Separation of control areas of Belgium, Denmark, Germany and Netherlands, which are the areas with a high penetration of EV chargers (14399 MW, which is more than 58 % of the entire interconnected area). It was considered that 10 % of charging stations are loaded and all connected EVs are capable to provide the desired frequency support. The power unbalance of the separated island was −5645 MW.

Simulation results – waveforms of frequency deviation for different types of EVs chargers response – are shown in Fig. 4.6.



(a) Spain and Portugal

(b) Belgium, Denmark, Germany and Netherlands

Fig. 4.6: Frequency deviation in the separated parts

As the simulated imbalance was large in both cases, frequency dropped quickly – it reached the critical value of 49 Hz quickly in modes of no support, step change and LFSM. The first stage of UFLS was activated (threshold value is 49 Hz) and after the tripping, the active power balance was recovered. The last mode – step change together with LFSM – provided sufficient dynamics and power reserve to stop the frequency drop. Frequency did not reached the critical value of 49 Hz, thus UFLS was not activated and consumers did not experience supply interruption.

Based on the results, it can be summarized that EVs charging stations are a suitable mean for frequency control. They have fast response, which provide dispatchers time to activate other reserves. On the other hand, they have limited time of use, given by the battery capacity and state of charge (or simply said, till the batteries are discharged). Further details can be found in the paper.

4.8 Paper #7: Use of New Means for Frequency Support of Power System in Emergency State

The use of EVs charging stations for grid frequency support was investigated in the previous paper. However, there are additional devices being connected to the power system, which can be used for providing frequency support. The growth of RES and their variable production, depending on the weather condition, brings the request for energy storage systems, such as BESS or P2G solutions [63]. If these devices are equipped with controllers responding to frequency deviation, they can provide the desired frequency support in emergency state.

We should not neglect also the support via HVDC links. The European power system is composed of multiple synchronous areas (e.g. CE, Nordic, Baltic etc.). These areas are interconnected with HVDC links as their synchronous parallel operation is not feasible [64]. HVDC links are used in normal power system operation, when the power exchange is contracted. However, HVDC links can be also used for support in emergency state, when the unaffected areas may provide support to the affected one and thus help to overcome the temporary problems there.

This paper analyses support of different means in the emergency state, regarding their dynamic response. The analysis has been done using the dynamic simulation model, which was a simplified model of (a part of) the power system, in the form of the single-bus equivalent model. Its schematic single-line diagram is shown in Fig. 4.7.

The model contains units with synchronous machines (hydro, nuclear, thermal and gas power plants), inverter-based sources (PVs, wind power plants), loads, and mainly means for providing frequency support – EVs charging stations, electrolysers (P2G), batteries and HVDC interconnections. The frequency response is modelled in a following way:

- **frequency containment process** is realized on hydro, thermal and gas power plants;
- **EV charging stations** have 3 different types of response (see Fig. 4.5): for one quarter, step change and LFSM mode is assumed (group EV1), another quarter has only the LFSM response (group EV2) and one half has no response (group EV3);
- **battery storage** has the response of step change and LFSM mode;

- **electrolysers (P2G)** operate in the LFSM mode (consumption is decreased with frequency deviation);
- **HVDC links** have the LFSM response (active power provision is increased with frequency deviation);
- **pumped-storage plants** make part of the special protection scheme, which means that they are equipped with underfrequency protection disconnecting them if they are in a pumping mode;
- **load** has the self-regulation effect of 2 %/Hz and it is equipped with UFLS protection scheme.

Further details about the dynamic models and their setting are described in the paper.

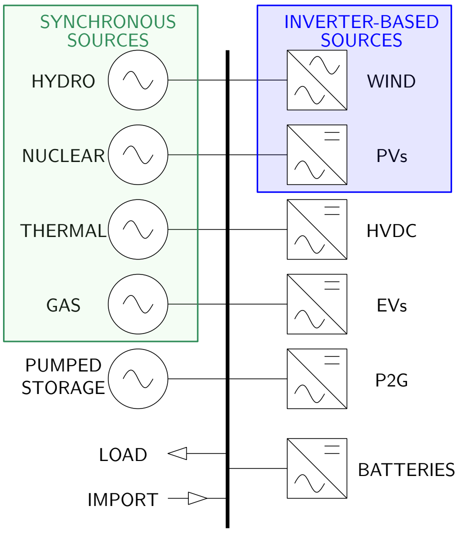
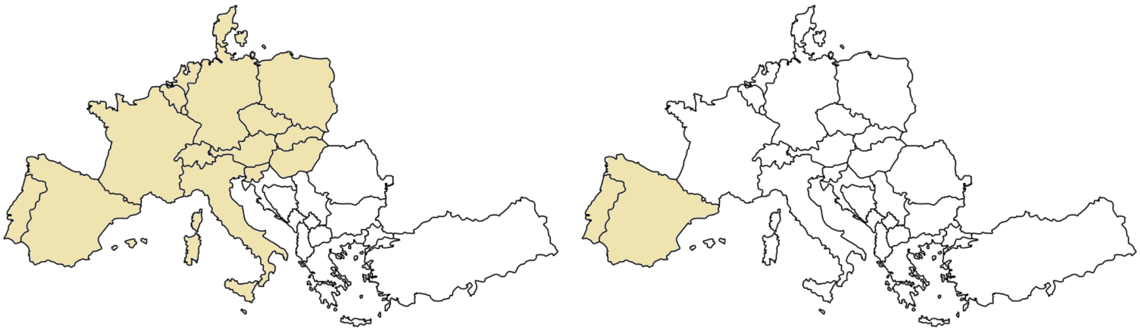


Fig. 4.7: Single line diagram of the dynamic model

To assess the behaviour (frequency response) of above-mentioned means, two simulation scenarios were prepared, both leading to the emergency state of power system occurrence (decrease of frequency under the value of 49.8 Hz). The first case was the separation of the North-West part of the CE synchronous area (alternatively, it can be seen as the separation of Balkan peninsula), and the second case was the separation of the Iberian peninsula. Separated areas are marked in Fig. 4.8 (highlighted, separated areas are power deficient). The choice of contingencies and scenarios is inspired by the real incidents from the European power system in 2021. However, the aim was not to replicate these incidents, but to investigate the behaviour of the future power system under similar conditions. Installed capacities were based on estimates for the year 2030 though. It is also worth noting that the locations of separations do not match exactly the ones from 2021, but they were moved to the borderlines.



(a) North-West

(b) Iberian peninsula

Fig. 4.8: Separated parts considered in the simulation

Starting with the separation of North-West area, the resulting unbalance was 5.8 GW (projected contingency is 3 GW). Despite that the frequency nadir reached only the value of 49.77 Hz ($\Delta f = -223$ mHz) and the steady-state deviation remained above the critical value of 49.8 Hz ($\Delta f = -200$ mHz) – see red curve (case with LFSM) in Fig. 4.9. The response of different types of devices can be observed in Fig. 4.10. Devices of which response is shown there (EVs, HVDC interconnections and batteries) are connected to the power system via the converter, allowing a quick response. It can be observed that the power unbalance is covered mainly from batteries, whereas a significant power provision through the HVDC links is activated only in the initial stage of disturbance.

To even better show the positive influence of use of EVs charging stations, batteries and electrolysers, two additional cases were simulated. The first one was no support from these devices (case without LFSM), and the second one was that the group of EV1 provides only LFSM support (case EV1 only with LFSM), when there is no step change (i.e. charging is not stopped, only decreased). Frequency deviation waveforms for these two additional cases are also shown in Fig. 4.9. From the results, it can be observed that the frequency deviation is significantly bigger comparing to the case with LFSM. In the worst case, without LFSM support, the nadir reaches the value of 49.63 Hz ($\Delta f = -370$ mHz).

The separation of Iberian Peninsula is a different case. Despite the contingency leads to the lost of only 2451 MW, the separated part is significantly smaller, thus have lower inertia and less reserves. In addition, there is no HVDC interconnection considered in Spain and Portugal, therefore this support cannot be taken into account. The same three simulation cases, previously described, were considered (without LFSM support, with LFSM support, and EV1 only with LFSM). Simulated frequency deviation waveforms are shown in Fig. 4.11.

The main benefit here is the suppression of UFLS activation (first step of UFLS is activated at 49 Hz), because that would mean the supply interruption for a part

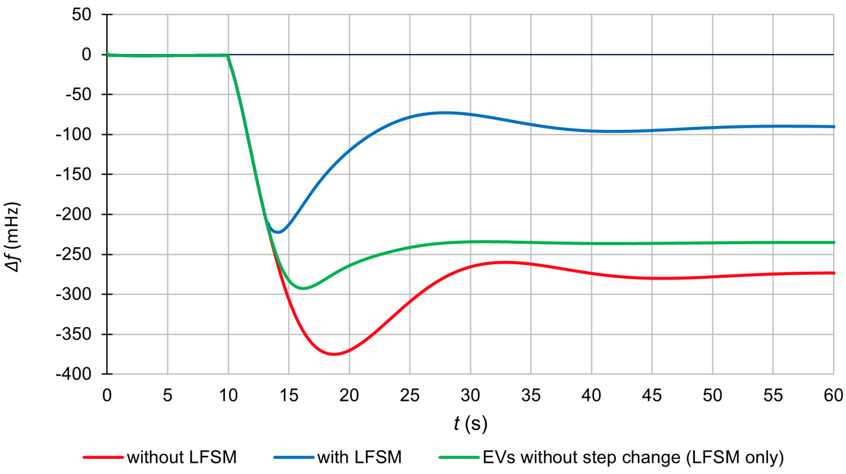


Fig. 4.9: Frequency deviation in the separated part – North-West area separation

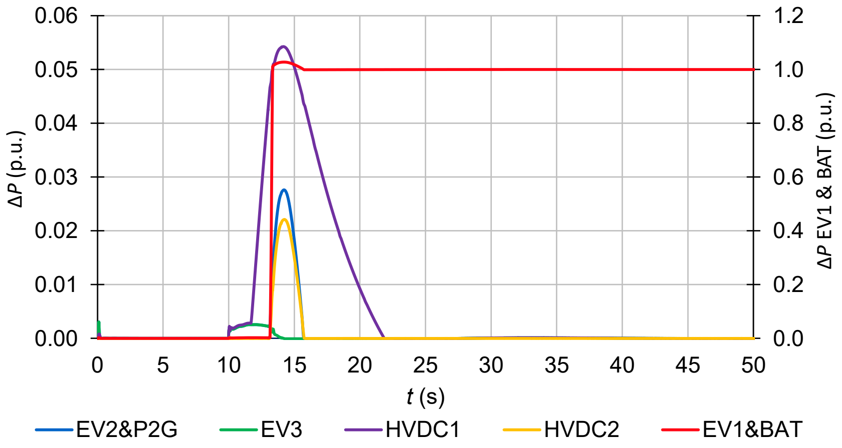


Fig. 4.10: Change of active power provision after disturbance – North-West area separation

of consumers. As the separated part is smaller, the frequency nadir is lower and the drop is faster, comparing to the separation of North-West area. For the case without LFSM, the first step of UFLS was activated when frequency reached 49 Hz. However, we can observe the undesired effect of overfrequency.

From the simulation results it can be seen that the support of these new means is very beneficial and needed – they can contribute to stabilize the system frequency and suppress the activation of UFLS. Their automatic activation also gives dispatchers time to activate other reserves. The increasing penetration of these devices in power systems brings the need for specification of requirements for connecting such devices to the power system. Last but not least, the paper also gives the idea on how to develop a simplified dynamic model for frequency stability studies and deter-

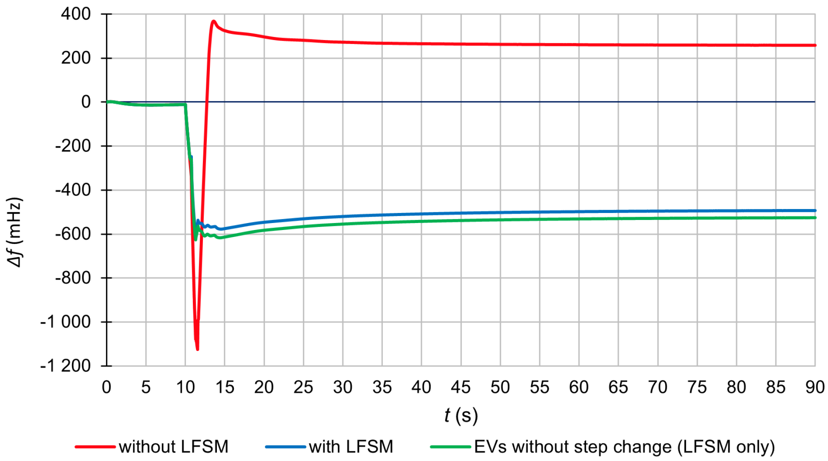


Fig. 4.11: Frequency deviation in the separated part – Iberian peninsula separation

mine its parameters. More detailed description of the simulation model and further results can be found in the paper.

4.9 Summary

The chapter presented three papers related to short-term frequency stability, which is being investigated within tenths of seconds after disturbance. Paper #5 was focused on creation of a single machine model for a simulation of the split of CE from January, 2021, and it showed how to obtain data necessary for modelling from publicly available resources. Paper #6 investigated the different strategies of support from EVs charging stations in an emergency state (specifically, for frequency decrease below 49.8 Hz). The results showed that charging stations are very suitable for providing the support, which can be exploited as their number increases. Finally, paper #7 presented a complex equivalent model, suitable for simulation of a future power system. The model included, except the conventional types of sources of loads, also new technologies suitable for frequency support, such as EVs charging stations, electrolysers and HVDC interconnection. The possible support of these means in an emergency case in the future power system was investigated, revealing that they can help maintain the frequency stability and even suppress the activation of UFLS. Nevertheless, UFLS remains an important issue and it is dealt with in more detail in the following chapter.

5 The Role of Under-Frequency Load Shedding

Frequency control processes, described in the previous chapter, are designed to maintain frequency stability, thus to maintain the frequency within the admissible range of 50±0.2 Hz. Various means for mitigation of contingencies resulting into the frequency deviation higher than 0.2 Hz have been also presented there. However, if none of these means can stop the frequency from falling, the last brake to avoid blackout occurrence is the activation of UFLS. The process of UFLS should be though properly designed and set in order it helps to solve the situation. Its activation should occur only in case of unavoidability, as it has the negative consequence of supply interruption for some consumers.

This chapter further explains the process of UFLS, specifies the current legislation applicable for it, and describes also the different schemes. Afterwards, selected paper about the response of UFLS system to different types of disturbances, is presented. At the end, the chapter presents current projects in this field.

5.1 Principle of Under-Frequency Load Shedding Operation

When power system is in emergency operation with a significant loss of production, thus a severe generation-load imbalance, conventional processes of frequency control are not able to reach new equilibrium with steady-state frequency deviation and the system is in risk of blackout occurrence, one of the last possibilities to stop the frequency drop and restore active power balance is to shed loads. Even though some consumers experience the electricity supply interruption, it is crucial to maintain the power system in operation (thus maintain frequency stability) instead of blackout occurrence and following need of power system black start and synchronisation of islands, which would take much longer time and effort, not speaking of economic and social impact of the blackout.

Conventional term of UFLS has been replaced by a new term of Low frequency demand disconnection (LFDD), but the basic principle has remained the same, of course. As UFLS is an established and still used term, it is kept further in this text. The process of UFLS has to be activated automatically (manual or operator initiated activation generally cannot be accomplished fast enough) using automatic protection relays installed in substations, which are disconnecting loads. These relays are implemented in high voltage or medium voltage substations (in distribution system, because usually, no end-consumers are directly coupled to the transmission system). This situation implies the need for cooperation between TSO and DSO. Usually, TSO sets the frequency thresholds and amount of loads and DSO implements the frequency protections in the network in order the requirements from TSO are met.

Although the basic principle of the UFLS process is really simple and clear, many questions arise regarding its settings – which amount of load should be shed in order the frequency stability is restored, and which criteria should be used for correct activation. Situation is getting complicated with the changes of network topology, when the amount of distributed energy resources is increasing and also other means for frequency support provision are being connected to the distribution system.

5.2 Load Shedding Techniques

Load shedding techniques can be sorted into 3 basic categories [65], based on the used algorithms:

- conventional load shedding techniques,
- adaptive load shedding techniques,
- computational intelligence based load shedding techniques.

Conventional load shedding techniques

Conventional load shedding techniques comprise under-frequency and under-voltage load shedding [65]. The second mentioned serves to protect the power system from voltage collapse, which is not in scope of this chapter, so we leave them away.

These conventional under-frequency load shedding is based on the frequency measurement. When the threshold is reached, the defined amount of load is switched off. This makes them easy to implement and it may be treated as a decentralized solution (frequency is measured locally in the substations). Algorithm has several steps with different thresholds and amounts of load to be disconnected.

The main disadvantage is that it is always maladjusted to the contingency, as the amounts of the load being disconnected are set in general, regardless the actual need. There may occur situations when too much or not enough load is shed, which can worsen the situation. Another the problem may be the load variation. Frequency protections ensuring the UFLS process are installed on defined high voltage or medium voltage feeders, which loading is not constant. Situation is even aggravated with the increasing share of distributed energy resources (mainly RES), which may completely change the power flows in the network.

Despite their drawbacks, conventional load shedding techniques are actually widely used in the power systems. Their use is ordered for all ENTSO-E members, as will be specified later.

Adaptive load shedding techniques

Adaptive load shedding techniques reflects the variation of generation and load during the year, trying to match the shed load to the contingency. Although, these methods use different indicator than the frequency deviation. Most commonly, it is the rate of change of frequency (RoCoF), of which use can be deduced from the previous discourse on frequency stability.

In the preceding chapter, the frequency stability modelling using the single machine equivalent was described, and the importance of swing equation (3.1) was highlighted. The equation can be modified into the form of (5.1), describing the dynamics of the equivalent machine. Now, the difference Δp (p.u.) is the power imbalance, f_n (Hz) is the nominal frequency, and the term of $\partial f/\partial t$ (Hz/s) is the RoCoF, the indicator used for the load shedding.

$$\Delta p = \frac{2H}{f_n} \cdot \frac{\partial f}{\partial t} \tag{5.1}$$

If we assume the inertia constant of the system is known, the equation (5.1) can be easily used to determine the power imbalance causing the change of frequency using the value of RoCoF ($\partial f/\partial t$), and thus identify the load that needs to be shed.

Although the use of this method may seem simple, it is fraught with many uncertainties. One can observe that the Δp is intentionally put to p.u., with a base of the power of the equivalent machine. This value, however, may not reflect the effect of load (this was discussed in section 4.1). Also, H is used as a constant of the system (this was also discussed in section 4.1), but, in reality, its value also varies, depending mainly on the number of machines providing inertia response being actually connected to the power system. Specifically, a problematic case is the separation of the system, when the inertia of separates, entered as a parameter to the equation, can vary a lot.

RoCoF-based schemes are recommended as an additional mechanism to the conventional load shedding schemes [66]. In practice, RoCoF is also used as an indicator for the islanding detection.

Computational intelligence based load shedding techniques

Recently, there has been a boom in the use of computational intelligence algorithms in various processes. Researchers are investigating the possibility of their use in a wide range of applications, and the process of load shedding is no exception.

The main motivation for use of computational intelligence based methods is the same as for the adaptive schemes – to provide the optimum amount of load being shed. There are various techniques being examined, such as artificial neural networks, genetic algorithms, fuzzy systems or particle swarm optimization [67]. Their application is usually verified on some type of test system (frequently the IEEE 39 bus system). All methods have advantages and drawbacks; some of them are revealed in [67]. The further improvement of these methods is still needed for a real-time application.

5.3 Requirements for Load Shedding in Continental Europe

The requirements for UFLS have been standardized for a long time. Focusing only on the CE, former regulation, namely Policy 5 of UCTE Operation handbook [68], set the requirements in the following way:

- load shedding can start at 49.2 Hz,
- a stepwise 50 % (in total) of the nominal load should be shed in the range 49.0 to 48.0 Hz,
- at 49 Hz, at least 5 % of total consumption should be shed.

Additional specifications were in form of recommendation.

The established concept was significantly changed by the implementation of a new regulation. Commission regulation (EU) 2017/1485 of 2 August 2017 [27], brought more requirements for the UFLS system, which are:

- starting mandatory level frequency: 49 Hz,
- starting mandatory level demand to be disconnected: 5 % of the total load at national level,
- final mandatory level frequency: 48 Hz,
- final mandatory level cumulative level to be disconnected: 48 % of the total load at national level,
- implementation range: ± 7 % of the total load at national level, for a given frequency,
- minimum number of steps to reach the final mandatory level: 6,
- maximum demand disconnection for each step: 10 % of the total load at national level, for a given frequency.

Despite the legislation [27] came into force in 2017, there was a transition period for implementation, which ended by the end of 2022. Currently, all TSOs in Continental Europe should have implemented the UFLS scheme complying with [27].

However, not all TSOs have made the current requirements publicly available, thus the current settings cannot be easily compared. At least, selected available schemes are presented in Fig. 5.1, from which it is clear that the actual UFLS settings vary a lot.

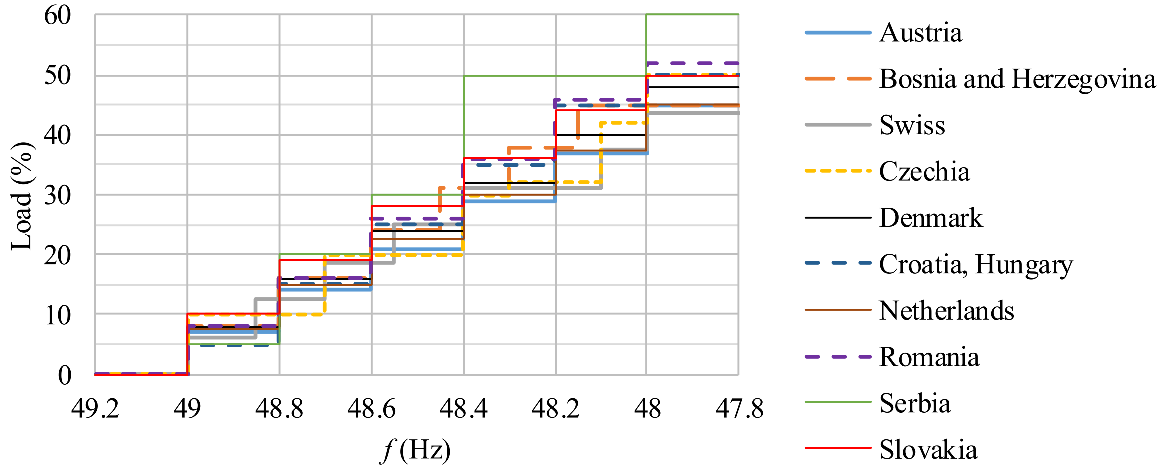


Fig. 5.1: Settings of under-frequency load shedding in selected European countries

5.4 Paper #8: Comparison of Decentralized and Centralized Under-Frequency Load Shedding

Significant frequency deviations, spreading through the system, are usually caused by large disturbances (e.g. outages of units, system splits), further referred to as the system wide disturbances. However, there can occur also local frequency deviations, caused by the local failures. Example of a local disturbance can be the islanding of a part of the distribution network due to the failure of the feeding transformer. The conventional UFLS, i.e. tripping of under-frequency protection, is triggered of the frequency measurement, thus it is impossible to differentiate between a system wide disturbance and a local disturbance. In such situation, supplementary algorithms are proposed to deal with the local disturbance.

In case when just a small part of the distribution system is separated, maintaining active power balance, thus frequency stability in the island may be problematic and it strongly depends of which sources and loads remained separated in the island. If there is a generation capacity, the active power balance may be met, but at the cost of shedding a much larger amount of load. For this purpose, the adaptive UFLS is beneficial.

The paper presents the testing of co-existence of two types of load shedding schemes. The first is the conventional one, based on the frequency deviation, denoted as centralized scheme. The second one is based on the RoCoF measurement and composed of several time-delayed steps, denoted as decentralized. The decentralized scheme used is a combination of conventional and adaptive technique, described in the previous section. It is RoCoF-triggered, but it is composed of several time-delayed stages, in which the defined amount of load is shed. Estimation of the exact amount of load to be shed is hardly feasibly because of a significant change of inertia due to separation.

The dynamic model used for the testing of proposed algorithms represented the central-east part of the CE synchronous area, comprising 8 control areas. Distribution network was modelled by the equivalent shown in Fig. 5.2 – as the aggregated loads and distributed energy resources. To test the influence of RES disconnection due to underfrequency, two cases were prepared: with and without RES.

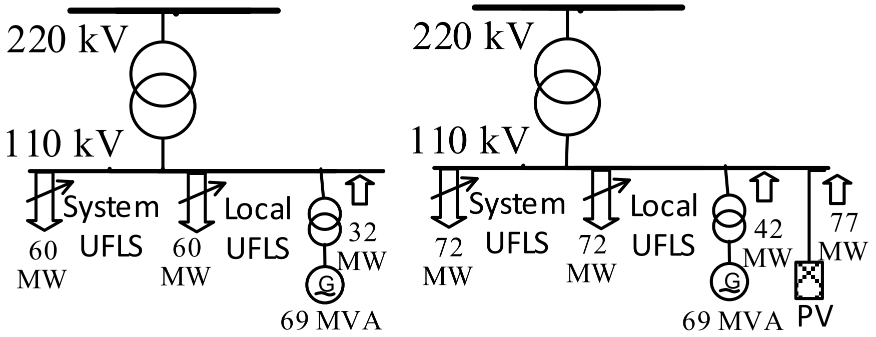


Fig. 5.2: Single-line diagram of the distribution equivalent network

The simulation was done for both types of disturbances. A split was chosen as a system wide disturbance, when a part of the system (one control area), exporting 4.5 GW, was lost. The frequency of in the remaining parts decreased below 49 Hz, thus the first step of conventional UFLS was activated. However, the adaptive load shedding was not activated. In case of local disturbance (islanding of the distribution system), frequency became to fall rapidly, thus all 5 implemented stages of system UFLS were activated, which would not be sufficient. Five out of seven stages of adaptive UFLS were also activated, which leaded to restoration of active power balance, and the frequency was stabilized with the steady-state deviation. The simulation was done also for a case of RES – photovoltaic being disconnected by the protection due to the under-frequency (the threshold was 49.5 Hz), when the adaptive UFLS was again successful and leaded to balance restoration in the separate.

Simulations demonstrated that both conventional and adaptive UFLS schemes can coexist and help to solve the issues of under-frequency for both system wide and local disturbance. Further details about the dynamic model and setting can be found in the paper.

5.5 Current Projects

It would seem that by introducing the legislation [27] with specified requirements for UFLS, the need for further investigation has died down. This is definitely not the case, mainly due to increasing share of RES.

In the Czech Republic, a strategic document of National Action Plan for Smartgrids (NAP SG), based on the Updated State Energy Policy, launched in 2019. The aim of NAP SG is to prepare and introduce new solutions to mitigate the problems of modern power systems, called smartgrids, that may anticipate in the future. The project covers a wide range of issues, both technical and economic.

One of the topics is also the process of automatic under-frequency load shedding and also the frequency support in an emergency state. Currently, the pilot projects focused on UFLS are being conducted. The project also focuses on the anticipation of large electricity consumers in the process of UFLS. The project outcomes are anticipated by the end of 2030.

5.6 Summary

The UFLS is a known and proven concept; requirements for its operation in the European network are specified in the legislation in a quite detail. The required UFLS schemes are conventional ones, but adaptive or computational intelligence based schemes get attention for their ability to optimize the load being shed. The selected paper #8 presented the coexistence of two different UFLS schemes, concluding that RoCoF-based scheme is suitable to mitigate the local disturbances (islanding), but it is beneficial also in case of system-wide disturbance. Main aims of a current research project of NAP SG are presented at the end of this chapter.

6 Conclusion

The thesis has dealt with the power system stability. The researched issues were presented in the form of comments and remarks to 8 selected papers, focusing on different topics. Thematically, they were split into three categories: transient stability, frequency stability and under-frequency load shedding. Outcomes, following in this chapter, are presented in the form of short answers to the research questions stated in the introduction. Main contribution is than listed. The last part is a brief reflection on future research in the field of power system stability.

Dissertation solution required a vast amount of literature review, computational studies and mostly simulations of various different cases. The thesis describe only the selected ones, whereas some others are described and presented in the published papers. The method used the most was the dynamic simulation on simplified power system models.

6.1 Outcomes

At the beginning of the thesis, 5 research questions were asked. The research presented in the thesis, published in individual articles, has provided answers to these questions. The following is a short summary of the presented findings.

1. Is it possible to calculate the value of critical clearing time, the indicator of transient stability, in a simplified way? How can its value be availed for on-line stability monitoring?

Research and study of simplified calculation formulas for CCT revealed that they may not achieve good accuracy, but they are suitable for estimation. The problem of CCT is related also to the on-line stability assessment, which is becoming more important due to the decreasing inertia of the power system. The method of extended two-port equivalent was described and validated, using both computational methods and time-domain simulations. The method is applicable for use in the power system operation; it has been already used by Czech TSO. However, analysis of various situations of power system operation revealed that there are special cases, which requires careful assessment, such as operation of generators and motors in the same bus.

2. How can the influence on stability of different factors be mathematically modelled? The question concerns both failures and different parts of a synchronous unit. What is their influence?

Despite the main stability indicator is CCT for the three-phase shunt fault, other types of faults occur in the power system and surely affects the transient stability. The model for transient stability assessment, using symmetrical components method, has been developed. It is applicable for different types of shunt and series faults. Various studies and sensitivity analysis on the developed model revealed interesting facts, e.g. the most severe unbalanced fault is the two-phase-to-ground fault, or the importance of zero sequence parameters, which should be precisely identified to get credible results from analysis. The overview of simulation possibilities of two different simulation tools has been presented, focusing on transient stability modelling. Building a detailed model is of importance, because it allows to take different factors into account, which may help to enhance the stability margin. These devices, such as fast AVR or PSS, are commonly used for this purpose in the power system operation, it is therefore needed to include them into dynamic models to obtain more realistic response.

3. How can simplified dynamic models for frequency stability analysis be built? How to find out their necessary parameters?

An important finding is that the analysis of a frequency stability of a really complex power system is feasible using a simplified dynamic model. For the tested case of a real incident, even the simplest SIME model brought pretty accurate results. In addition, the relevant data sources, suitable for building dynamic models, were identified and they might serve to other researchers willing to study this issue. A common problem is that it is not possible to acquire relevant data on the power system. The use of these resources partially or completely eliminates this problem. The SIME model is, however, not sufficient for investigation of dynamics of different sources. For this purpose, other models were created and presented.

4. How to benefit from new technologies for the purpose of frequency control in an emergency state of the power system? What should be their desired response?

The help of new means, which are EVs charging stations, P2G solutions or HVDC interconnections, can solve the problems of under-frequency in the emergency state. As the inertia in the power system is decreasing, and the frequency response is faster, the help of these means will be suitable to prevent the UFLS activation. The increasing share of these means (especially EVs charging stations) leads to a recommendation to contract this support within its connection in order to use their possibilities. Especially for EVs, the grid support is currently not provided.

5. What are the applicable algorithms and approaches for under-frequency load shedding? Which problems are they able to solve?

There do exist basically two concepts – conventional schemes, shedding the defined amount of loads, or adaptive schemes, trying to optimize the amount of shed load. The presented approach combined the conventional scheme with a RoCoF-based scheme. Dynamic simulation has proven the possibility of this concept to solve both global and local disturbances. Due to the already mentioned inertia reduction and transients fastening, the importance of tracking the RoCoF will increase.

6.2 Contribution

The main contribution of the presented research can be seen in the following items.

1. The method extended two port equivalent for DSA, has been validated. It is currently applied in practice by Czech TSO.
2. Models suitable for transient stability assessment in case of unbalanced faults, based on symmetrical components, has been developed.
3. Simulation possibilities of MODES and PSCAD simulation tools in the field of transient stability assessment has been described, giving the other researches idea how to use them for such simulations.
4. The possible support of new means and their positive impact on frequency stability has been demonstrated. The findings should open the question of its practical implementation, because especially EVs currently do not provide V2G support. Advice is not to miss the opportunity to contract their support, which should be done when they are connected to the power system.
5. Dynamic model for frequency stability studies has been built. The modelling approach shows how to overcome the obstacle of data acquisition by using publicly available databases and standard dynamic models.
6. Presented RoCoF-based UFLS scheme is able to solve problems for both system wide and local disturbances.

6.3 Future Research

The share of RES will continue to increase, thereby increasing the need of assessment of new types of stability (converter-driven and resonance stability). It seems that FACTS devices can play a positive role in this direction, therefore further operational experience will be needed. The increase of RES together with decommissioning of conventional plants will lead to already many times discussed inertia reduction. Faster transients will require faster response, mainly from BESS or batteries of EVs charging stations, for which appropriate legislation should be prepared to benefit from their support.

There is currently a major change in network topology, when not only the EVs, but also RES are being connected to the distribution systems. These systems are then facing a significant change of power flows, which may lead to voltage stability issues, power quality problems or malfunction of UFLS process.

One must also not forget the development of communication technologies, allowing new control methods to be applied. E.g., the demand-side response may find application in the field of stability. On the other hand, cybersecurity is becoming the topic of today and the future.

To sum up, even from this reflection, it is clear that the power system stability is still a topical issue. It has been investigated since the beginning of electrification, and there is no sign that new issues in this area will cease in the future.

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Symbols and abbreviations

f	Frequency	(Hz)
f_n	Nominal frequency	(Hz)
f_{COI}	Frequency of the center of inertia	(Hz)
t	Time	(s)
t_c	Critical clearing time	(s)
E_{kin}	Kinetic energy	(J)
H	Inertia constant	(s)
H_{syn}	Inertia constant of the power system	(s)
P_0	Mechanical power	(W)
P_e	Electric power	(W)
P_{LOAD}	Power of the load (consumption)	(W)
P_{M2}	Transfer capacity during the fault	(W)
S_n	Rated apparent power	(VA)
T_M	Mechanical time constant	(s)
α	Fault location coefficient	(–)
δ	Load angle	(rad)
δ_c	Critical angle	(rad)
ω_0	Synchronous angular speed	($\mathrm{rad{\cdot}s^{-1}}$)
Δf	Frequency deviation	(Hz)
Δp	Per unit active power imbalance	(p.u.)

aFRP	Automatic Frequency Restoration Process
aFRR	Automatic Frequency Restoration Reserves
mFRP	Manual Frequency Restoration Process
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
CCT	Critical Clearing Time
CE	Continental Europe
COI	Center of Inertia
DSA	Dynamic Stability Assessment
DSO	Distribution System Operator
EAC	Equal Area Criterion
EPC	Emergency Power Control
ERAA	European Resource Adequacy Assessment
EU	European Union
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission Systems
FCP	Frequency Containment Process
FCR	Frequency Containment Reserves

FRP	Frequency Restoration Process
FRR	Frequency Restoration Reserves
HVDC	High Voltage Direct Current
LFDD	Low Frequency Demand Disconnection
LFSM	Limited Frequency Sensitivity Mode
NAP SG	National Action Plan for Smartgrids
PSS	Power System Stabilizer
PV	Photovoltaic
P2G	Power to Gas
RES	Renewable Energy Source(s)
RoCoF	Rate of Change of Frequency
RR	Replacement Reserves
RRP	Reserve Replacement Process
SIME	Single Machine Equivalent
SMIB	Single Machine Infinite Bus
STATCOM	Static Compensator
TCSC	Thyristor Controlled Series Compensator
TSO	Transmission System Operator
UFLS	Under-Frequency Load Shedding
UPFC	Unified Power Flow Controller
VSG	Virtual Synchronous Generator
V2G	Vehicle to Grid

A List of Papers

References and links for the selected author's papers discussed in the thesis are given below, with specifitaion of repository and licensing.

Paper # 1

KOUDELKA, Jan; BÁTORA, Branislav and TOMAN, Petr. On Direct Calculation of the Critical Clearing Time. Online. *Elektrorevue - Internetový časopis.* 2019, vol. 21, no. 5, p. 134-139. ISSN 1213-1539. Available from: `http://hdl.handle.net/11012/214192`. [Accessed 2023-08-30].

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Paper # 3

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Paper # 6

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Paper # 7

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Paper # 8

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