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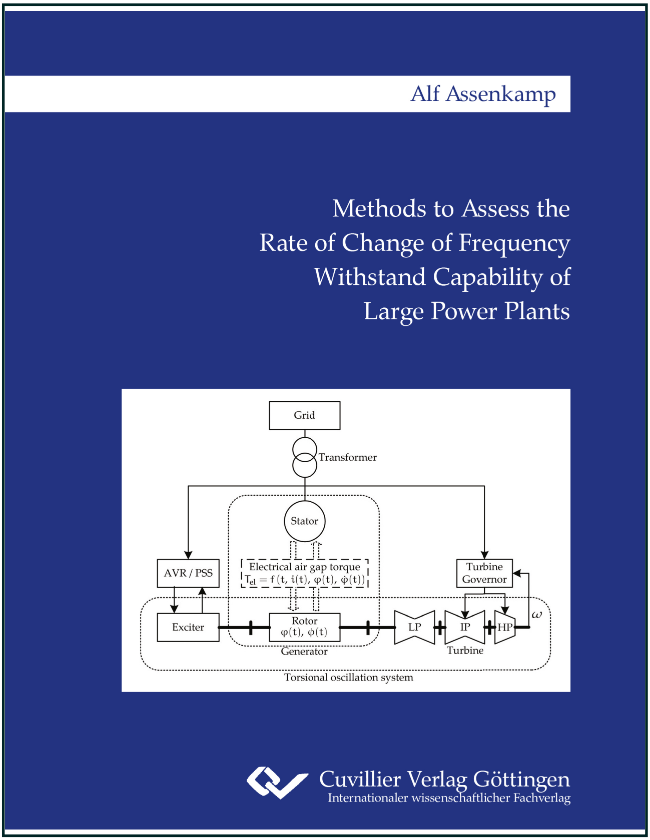
Methods to Assess the Rate of Change of Frequency Withstand Capability of Large Power Plants



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1 INTRODUCTION

1.1 MOTIVATION

The energy sector plays a major role in the global reduction of greenhouse gas emissions [1]. The resulting transition of power systems with integration of wind farms and solar plants as well as building of new transmission lines changes the structural design of the systems. Furthermore, power system stability and control is affected by increasing non-synchronous generation.

Turbo generators and salient pole hydro generators are connected via a step up transformer to the power system. They produce the grid frequency and are coupled electromagnetically to the power grid. This coupling and resulting forces are study topics since the beginning of electric power transmission.

Following the loss of a large generating unit within the power system, the resulting load overflow in the system is balanced by rotational energy from coupled synchronous generators with large turbines and respective high inertia. As a result, frequency of these machines drops. In Figure 1 active power output and line frequency of a 400 MW turbo generator are shown, as actually measured after trip of a large in-feeder from a power system.

The control system reacts by increasing electric power production, so that after a few seconds a new constant grid frequency should be reached. Loss of a large load results in a frequency rise respectively. The electromechanical torque induced at the air gap of the generator due to the fault induces torsional vibrations in the shaft system. At the same time, the electromechanical coupling stabilizes grid frequency.

Photovoltaic power stations have no rotating components and wind farms are typically connected to the grid via frequency converters. Thus, there is no electromechanical coupling of rotating inertia to the grid frequency.

Because of that, stabilizing inertia in power grids worldwide currently decreases significantly, although synchronous machines will have a huge share of in-feed in the future, e.g. as hydro generators and turbo generators in biomass, geothermal, nuclear fusion, synthetic natural gas, and concentrated solar power systems. Especially in situations of high wind and low energy consumption, only very few synchronous machines will be synchronized with future power systems. This generation situation is called low inertia grid. Within a low inertia grid consequently the rate of change of frequency (ROCOF) after a given grid fault increases compared to high inertia grids.

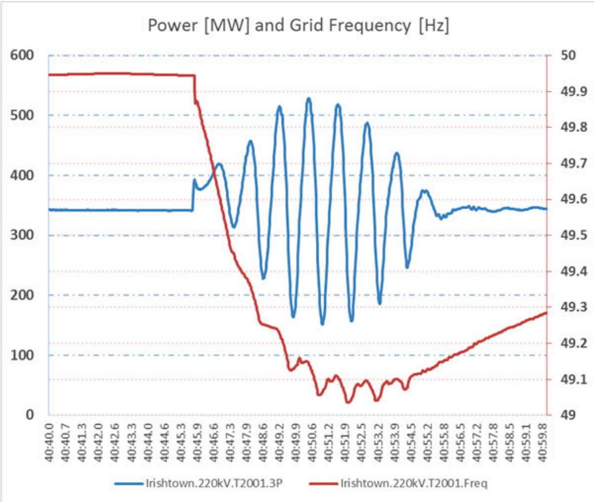

Figure 1: Active power (blue, left scale) and line frequency (red, right scale) of a synchronous machine, real time [min:sec] [2]

With rising integration of wind power and other non-synchronous in-feeders, the power grid of the future needs new measures of frequency stabilization [3] and it will become necessary for power generators to tolerate severe frequency instabilities.

In the current situation, events with high ROCOF values are already present, as shown in Figure 1. Furthermore, the problem is that no standards exist to analyze the effect of transient disturbances with high ROCOF on synchronous machines.
Typical power system faults, that synchronous machines are designed to withstand, are short circuits or fault synchronization with several fault angles. All of these faults assume a constant grid frequency and a fault electrically close to the generator under analysis.

Assuring the connection of synchronous machines during severe ROCOF events helps stabilizing power systems during the ongoing energy transition towards a decarbonized power sector.

But also in these future systems, not all generation will be based on inverters. Synchronous machines will still be connected to the system and produce energy in hydro power plants and gas turbine plants. The latter will potentially be fired with hydrogen or methane produced by power to gas technologies. Knowing, which frequency transients a synchronous machine can tolerate will consequently also help stabilizing and planning decarbonized power systems.

A severe ROCOF event caused a widespread power outage in South Australia on 28 September 2016 [4]. At the same time, plant operators face new regulations obliging them to keep their synchronous generators connected to the power system during such events [1].

As it is not clear, how the ability of generators to tolerate such events can be tested reliably, an optimized methodology for this is urgently necessary. Faults that are tested during design of synchronous machines can no longer be seen as covering the effects of severe ROCOF events. This assumption was valid for power grids, where frequency deviations occur seldom and with small ROCOF only.

Within this thesis, methodologies for ROCOF studies are developed and tested with regard to differences between synchronous machine behavior in low inertia grids and fixed frequency grids. Furthermore, the stability and life time consumption are assessed.

1.2 AIM OF THE THESIS

It is not clear for many types of electrical machines, if they are capable to withstand events with high ROCOF, without losing synchronism or disconnecting from the power system, because such faults are typically not considered during design and commissioning. Loss of synchronism can occur within one or two swings of pole angle, if resulting oscillations of electrical values go beyond transient stability limits. Furthermore, the control system of the machine might act counterproductive and worsen occurring oscillations of electrical values leading to loss of synchronism after a few swings of pole angle. Disconnection from the power system can be caused by the generator protection system, which can lead to a cascade of trips in the worst case.

Furthermore, the mechanical part of the problem needs to be assessed. If the machine is electrically capable to stay connected and synchronized to the system during the event, mechanical loads on the synchronous machine could be significant and cause damage or fatigue.
The question arising is how severe the effect of events with high ROCOF rates is compared to the effect of typical electrical faults considered during machine design as detailed in [5]. These are briefly called *design cases* in the following. It cannot be said, if the entire turbine shaft might be endangered by the events, or components belonging to it. These might be couplings or turbine blades. Strong accelerations of the rotor due to the events might even lead to slipping of the rotor end bell or tooth top cracking. Also the foundation bolts are subject to forces, which may put them at risk. Furthermore currents through end windings may cause forces resulting in fatigue or damage.
Also frequency of ROCOF events has to be taken into account. Even if torsional mo-

ments and resulting fatigue are lower for a single event compared to design cases, it has to be clarified, if due to the large number of events, a power plant may suffer during it's life time, a possible shortening of life time or outage frequencies is tolerable for existing machines. For new plants, a consideration of ROCOF events during the design phase might become necessary in addition.

These considerations show the need for detailed assessments regarding the effect of ROCOF on synchronous machines. No test procedures for severe ROCOF events exist so far. Besides that, the weak points of synchronous machines regarding these events are not clear. The development of a general procedure for these assessment and a road map for further investigations are urgently necessary.

Within this thesis, detailed methodologies are developed with regard to:

1. Power system models for ROCOF studies;
2. Electrical ROCOF studies;
3. Mechanical ROCOF studies.

The methodologies are then assessed with a detailed power system model setup, electrical ROCOF studies for nine and mechanical ROCOF studies for two different synchronous machines.

1.3 STRUCTURE OF THE THESIS

The structure of this thesis, as detailed in the following, is shown in Figure 2 at the end of this section.

In Chapter 2, at first the state of the art with regard to dynamic behavior of synchronous machines with a focus on the mechanical effects of electrical faults is provided initially. Following that, it is described, which investigations on the topic of power systems with little in-feed by synchronous machines, called low inertia grids, are performed.
Subsequently, the theoretical foundations for studying ROCOF and its effects on synchronous machines are developed in detail. To work out, how power system behavior changes due to the energy transition, it is important to understand how electric power systems work and how electrical machines and power systems can be described mathematically. Furthermore it is important to understand, what ROCOF events are. Modern transmission systems are huge and it is necessary to have techniques at hand to reduce the number of nodes in a power system model significantly. Finally, the electromechanical coupling as the main reason for forces and torques within the generator and turbine of a synchronous machine is detailed to draw conclusions on endangered components.

In Chapter 3 the methodology to set up power grid models to investigate ROCOF events is developed. It is important to develop a purpose dependent approach, because possible models differ significantly in size and structure. For a ROCOF study with a given line frequency excursion it can be sufficient to set up a system with two generators and an infinite bus system. For the determination of such ROCOF traces, whole transmission system models might be necessary. With the methodology developed, the correct decision for the specific case can be determined and the respective model can be set up.

In Chapter 4 the methodology for electrical ROCOF studies is developed. An analysis is performed with regard to appropriate generator models and it is explained, how these can be validated. Following that, recommendations are given, such as which analyses should be performed and what the evaluation criteria should be. Furthermore evaluation and optimization techniques for the control and protection system are developed. With the methodology developed from these considerations it is possible to assess whether a synchronous machine is electrically capable to withstand a ROCOF event.

In Chapter 5 the methodology for mechanical ROCOF studies is developed. If a machine is electrically capable to withstand a ROCOF event, it might be worth investigating, if this is recommendable from a mechanical point of view. Diverse investigations with huge effort can be performed to analyze this. Therefore it makes sense, to develop a methodology, that starts with simple benchmarks based on comparison of ROCOF events with electrical faults typically considered during machine design, like short circuits and fault synchronizations. This way it is possible to perform deeper analyzes only when a concrete threat has been recognized. With the methodology, the important question can be answered, if effects of repeated ROCOF events are tolerable throughout designated life time.

In Chapter 6 the methodologies are applied to test systems and machines. A full grid model set up is described and analyzed and validated with regard to ROCOF values occurring after system faults. Reduction techniques described in the methodology are exemplified on this system, leading to reduced order systems that can be used for ROCOF studies. The electrical ROCOF study methodology is tested with models of nine example machines that are subjected to diverse ROCOF frequency traces. Results are validated by comparison with ROCOF studies in reduced grid models and by applying COMTRADE files to the machines directly. Furthermore, the mechanical ROCOF study methodology is applied to two turbo generators. The recommended benchmark results are validated by in-depth analyses of shaft systems and turbine blades. The most important results are collected and interpreted.

In Chapter 7 conclusions are drawn and the way forward to future investigations is shown.

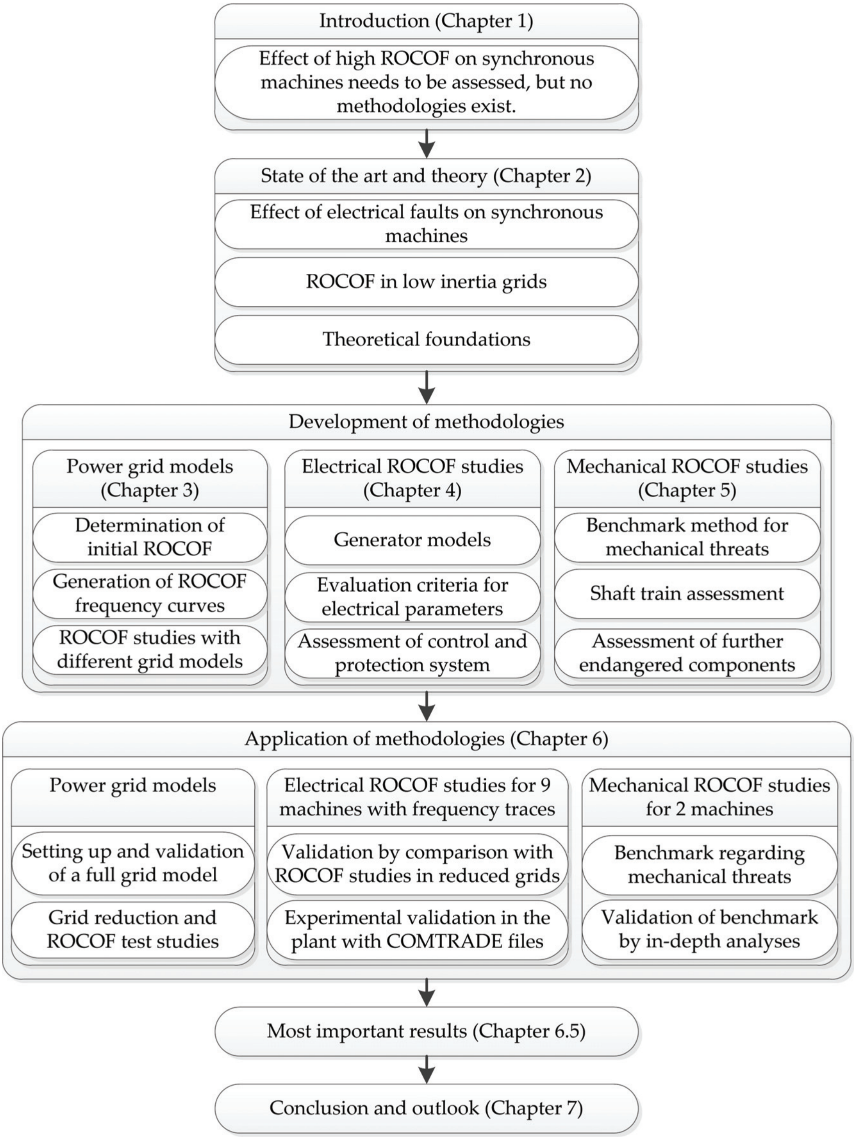

Figure 2: Structure of the thesis

2 STATE OF THE ART AND THEORY

2.1 OVERVIEW

Within this chapter, the state of the art and theoretical foundations of investigated components and applied tools for the performed investigations are detailed.
Severe ROCOF events need to be assessed for diverse existing turbo generators and large machines coupled directly to the power system. Therefore, electrical quantities resulting from such events should be analyzed thoroughly and compared to those from faults considered during design of machines.
It is therefore necessary to have an understanding of electric power systems as well as of synchronous generators.
Due to the electromechanical coupling of the shaft train to the stator via the airgap torque T_{el}, ROCOF events do not only cause swings of electrical quantities, but also lead to forces within several components of the generator and the turbine.
To assess the mechanical effects of ROCOF events on the machines, a broad range of analysis techniques is consequently necessary. To keep the text short, for diverse techniques only a brief introduction is given with reference to literature detailing the topic.

In Section 2.2 a brief historical overview with regard to the investigation of severe faults on large synchronous machines is presented.
In Section 2.3 the state of the art concerning ROCOF studies is described.
In Section 2.4 the theoretical foundations are detailed as follows:
In Section 2.4.1 an overview of electric power systems is given, which is necessary for comprehension of frequency stability issues in power grids.
In Section 2.4.2 the mathematical description of synchronous machines and how to represent those in ROCOF studies is derived. Apart from mathematical machine models, control and protection functions have to be implemented in a suitable manner.
In Section 2.4.3 basics of power flow analysis are detailed. Power flow analysis is necessary to balance and validate power grid models thoroughly for ROCOF studies.
In Section 2.4.4 the scope is widened to the foundations of transient stability studies. The underlying question is how to compute severe grid faults resulting in large ROCOF in a realistic manner with appropriate programming and computation time efforts. The most simple approach is an infinite bus system. For transient stability studies, like ROCOF studies, this is not sufficient, and larger grid models need to be set up.
In Section 2.4.5 the principles underlying ROCOF events are described. The term ROCOF is defined, principles of frequency instabilities are deduced and a simple formula for estimation of initial ROCOF after a grid disturbance is provided.
It has to be taken into account, that the reaction of a synchronous machine to a grid

fault depends on the power grid it is connected to. Realistic representations of current power grids cannot be set up easily, because many data, like definite settings of control and protection systems are not available in many cases. Furthermore the effort of setting up a transmission system model of a whole country or region in all detail is enormous. Therefore it is absolutely necessary to develop suitable reduced grids for ROCOF studies. The theoretical background necessary for this is developed in Section 2.4.6.
In Section 2.4.7 the potential mechanical consequences of ROCOF events on the system turbine and generator including belonging components are deduced.

2.2 EFFECT OF ELECTRICAL FAULTS ON SYNCHRONOUS MACHINES

Transient behavior of power systems is a topic of research since more than 100 years. Steinmetz published a standard work *Transient Electric Phenomena and Oscillations* [6] in 1909. Methods to calculate torques in synchronous machines have been developed in the 1920s, such as [7]. Around 1940 investigations focused on short-circuit torques in synchronous machine shafts, such as [8].

Calculations for further electrical faults as well as fatigue calculations for the shaft train came up in the 1970s. Joyce, Kulig, and Lambrecht published investigations on "Torsional Fatigue of Turbine-Generator Shafts Caused by Different Electrical System Faults and Switching Operations" [9] in 1978. Torsional stresses in large steam turbo generator shafts due to both planned and unplanned switching operations are discussed.
Therefore, different types of failures are analyzed in-depth with fixed-frequency grid models. As a result they show, that torsional moments depend strongly on fault clearing times. From deduced periodic occurrences of maximum torsional moments life time consumption is calculated. Damping factors prove to have large influence. Furthermore, it is shown, that the fault location has a significant influence on residual stress at nodes with high loads. Finally, a list connecting life time consumption with several faults is derived.
The publication is a valuable foundation for evaluation of the effect of grid failures on synchronous machines, as the methods applied connect the electrical machine model with mechanical forces and fatigue. Within this thesis the effect of grid failures, which produce high ROCOF that [9] does not contain are assessed. Also, no investigation of effects on shaft train components, such as the rotor end bells is performed in [9].

Also in [10] grid faults and the effect on turbo generators are investigated. The focus lies on mechanical coupling moments and resulting fatigue. Investigated influencing variables are the short circuit power of the grid, fault clearing times, residual mechanical stresses, as well as the location of failure.
It is derived, how torsional moments depend on the short circuit power of the grid. High short circuit power of the grid results in high compensating currents. These produce high compensating torques. One conclusion is, that residual stresses

positively correlate with the short circuit power of the grid. This leads to acceleration of the rotor.
Another result of interest is the dependence of occurring forces on the underlying power system. Maximum moments are smaller, when the generator feeds into two separated busbars. Furthermore, stability for different fault clearing times is enhanced. Regarding fault clearing strong dependencies between moments and the timely sequence of fault clearing events are derived.
As above, valuable insight into the effect of grid disturbances on the shaft system of large synchronous machines is provided. The methods presented are an important basis for the evaluation of events with high ROCOF values.

2.3 ROCOF IN LOW INERTIA GRIDS

In the current decade, ROCOF has become an increasingly studied topic, because the inertia synchronized with the power systems has fallen sharply, especially for high wind scenarios with low demand.

The EU Commission Regulation 2016/631 [1] demands consequently, that Transmission System Operators (TSO) need to define ROCOF values for which power plants need to stay connected to the system and operating. Corresponding challenges for whole transmission systems and for different types of in-feeders are therefore current research topics.

Island grids in highly industrialized countries experience the challenges at first. Publications based on ENTIRE TRANSMISSION SYSTEMS are correspondingly available based on power grids of the Island of Ireland, the main island of the UK, Australia, and Denmark.

In "Studying the Maximum Instantaneous Non-Synchronous Generation in an Island System; Frequency Stability Challenges in Ireland" [11] by O'Sullivan et al. high and ultra-high wind penetration scenarios are examined.
Models are set up using manufacturer data. The studies are performed as dynamic simulations with PSS/E. Line frequency after grid faults is compared for four geographically distant nodes.
Within these scenarios, the focus lies on impact of largest in-feed loss and network fault induced wind turbine active power dips for two transmission system scenarios; 2013 and 2019. For these cases, a variety of system conditions is assessed with respect to mitigation measures. For the investigated scenarios, the most effective measures to mitigate frequency stability risks result to altering ROCOF protection and emulated inertia measures.
The study treats the system from a frequency stability point of view. Therefore, it is a valuable study regarding mitigation measures. Loss of synchronism or connection of synchronous machines connected to the power system are not investigated.

In “Investigation of non-synchronous penetration level and its impact on frequency response in a wind dominated power system” [4], Nahid-Al-Masood et al. describe effects of low-inertia due to high penetration with renewable, especially wind, as for *South Australia*. Origin of study efforts is a widespread power outage on 28 September 2016.
The wind farms and a high voltage direct current (HVDC) interconnection to the adjacent state Victoria often contribute to a high level of non-synchronous generation in South Australia. Frequency control can be disturbed significantly after grid faults in cases of high import from Victoria via the HVDC line, which also has no means to stabilize grid frequency, and high wind penetration. Resulting ROCOF could lead to frequency deviations outside of tolerable frequency ranges with load shedding and tripping of machines from the system.
The paper assesses the non-synchronous penetration level in South Australia and investigates its effect on power system frequency response. It also estimates the maximum allowable non-synchronous penetration level after an interconnection trip to minimize load shedding and keep the ROCOF acceptably low.
The approach concentrates on underfrequency load shedding mainly. A detailed analysis of the electrical machines, that could reveal further causes for tripping, such as pole slip, and mechanical analyses are not performed.

“Frequency stability improvement of low inertia systems using synchronous condensers” [12] is written in the context of the Danish long-term strategy to achieve a fossil fuel free country by the year 2050. Based on the future *Danish* power grid, which depends on few synchronous machines for frequency control, frequency stability is investigated.
Similar than for the All Island Grid of Ireland, the Western-Danish system is supposed to have mainly wind as renewable energy resource. Different scenarios of wind penetration, governor responsibility of synchronous generators, and the consequences of grid faults on the system frequency are assessed. The aim is to examine the impact of high-level renewable energy integration.
Finally, the effect of synchronous condensers as mitigation measure is examined. The authors conclude, that performance is satisfactory with regard to system frequency stability.
The remaining synchronous generators in the system are not investigated in-depth. This leaves room for the question, how they would react to such disturbances. Further stability problems that could evolve from potential disconnection of remaining synchronous machines or effects on fatigue and lifetime are not considered.

Different methodologies for supporting system frequency in low inertia power systems with HVDC lines are discussed by Huang and Preece in “HVDC-based fast frequency support for low inertia power systems” [13].
HVDC lines are analyzed with regard to their ability of providing frequency stability between Great Britain and the Continental European power system. Different frequency support control schemes including droop control and the exchange of