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Power System Restoration After a System Level Blackout

Measures for system operation to manage technical uncertainties during the bottom-up restoration of a transmission network

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PREFACE

The journey towards this doctoral thesis has been full of coincidences. I started working with power engineering related issues in 2008 when I started working as a trainee for Fingrid. In 2014, I started working in the system operations and got an opportunity to participate in a project related to Finnish power system restoration practices. This project was a major trigger for this research work, and I feel privileged getting the opportunity to learn and work with highly competent people within such an interesting research theme.

I have been working with many people during these years and I am grateful to everyone I have worked with. First, Prof. Pertti Järventausta, who also is the responsible supervisor of the work, deserves my warmest gratitude. Also, I am grateful to my supervisors Prof. Sami Repo and Doc. Tuomas Rauhala.

I want to express my deepest gratitude to Arto Pahkin for all the encouragement and support during this research work. Also, I am grateful to Timo Kaukonen and Dr. Liisa Haarla for the ideas, discussions and support during this work. In addition, I want to express my gratitude to Dr. Michael Weixelbraun for the discussions and ideas. This thesis would not exist without the support and discussions with Arto, Timo, Liisa and Michael.

I am also grateful to Antti Kuusela, Minna Laasonen, Antti Harjula, Dr. Janne Seppänen and Dr. Jukka Turunen for the invaluable discussions and excellent co-operation during these years. Also, I want to express my gratitude to Maarit Uusitalo, Nina Kujala and Reima Päivinen for all the support. I am also grateful to all my colleagues and my employer Fingrid for enabling and supporting this work.

Most importantly, I want to thank my family and friends for the support and encouragement during these years. Especially, I would like to thank my parents Marjatta and Esko, my wife Sanna and our son Onni for all the love and support throughout the years.

Tampere, 31 January 2022
Antti-Juhani Nikkilä

ABSTRACT

Societies have become increasingly dependent on electricity. If a blackout occurs, the utilities must restore the electricity system back to normal operation as soon as possible. Therefore, fast and robust system restoration is important.

This thesis studies the technical uncertainties related to electrical phenomena and protection and automation systems during transmission network restoration. This thesis focuses on a system level blackout. In this situation, the restoration is performed using a bottom-up approach. Consequently, the network being restored is extremely weak and prone to issues seldom encountered during normal operation. As the thesis shows, the uncertainties may delay or even prevent restoration using specific restoration paths. Therefore, the utilities must manage and mitigate the uncertainties in restoration planning and when restoring the system from a blackout.

This thesis proposes a restoration planning process to identify and manage the uncertainties. In addition, this thesis presents measures to manage four unwanted electrical phenomena during restoration: black-start generator self-excitation, harmonic resonance during transformer energization, parallel line resonance and ferroresonance and subsequent sustained parallel resonance.

This thesis shows that simulations alone are not sufficient for the identification of the uncertainties related to system restoration. Therefore, restoration field-tests are a mandatory part of the restoration planning. However, testing only the black-start generator is not sufficient. In addition, the restoration field-tests must always include the restoration of the initial transmission network which allows the connection the black-start generator with consumption and other generation.

This thesis shows that simulation models tuned for normal system operation are not suitable for restoration studies since the dominant system dynamics during restoration are significantly different than during normal operation. Thus, sufficient measurements during field-tests and actual restoration actions are required to capture system dynamics and calibrate simulation models for restoration studies.

Restoration procedures may be unconventional and significantly different than normal system operation. Therefore, the restoration procedures must be properly planned, validated with field-tests and trained regularly for the operational personnel.

TIIVISTELMÄ

Yhteiskunnat ovat yhä riippuvaisempia sähköstä. Häiriötilanteissa verkkoyhtiöiden tulee palauttaa sähkövoimajärjestelmä normaaliin tilaan mahdollisimman nopeasti. Tämän vuoksi järjestelmän nopea ja luotettava käytönpalautus on tärkeää.

Tämä väitöskirja tutkii sähköisiin ilmiöihin ja suojaus- ja automaatiojärjestelmiin liittyviä epävarmuuksia sähkönsiirtoverkon käytönpalautuksen aikana. Väitöskirja keskittyy sähkövoimajärjestelmän laajuisiin häiriöihin, jolloin käytönpalautus suoritetaan alhaalta ylös menetelmällä. Tällöin sähkövoimajärjestelmä on heikko ja altis ongelmille, jotka esiintyvät harvoin normaalin käytön aikana. Väitöskirjan tulokset osoittavat, että tutkitut epävarmuudet voivat viivästyttää tai jopa estää käytönpalautuksen. Tämän vuoksi verkkoyhtiöiden tulee hallita ja pienentää käytönpalautuksen suunnitteluun ja sen suorittamiseen liittyviä epävarmuuksia.

Tässä väitöskirjassa esitetään sähkönsiirtoverkon käytönpalautuksen suunnitteluprosessi, joka pyrkii tunnistamaan ja hallitsemaan epävarmuuksia. Lisäksi väitöskirjassa esitetään toimenpiteitä neljän ei-toivotun sähköisen ilmiön hallitsemiseksi palautuksen aikana: pimeäkäynnistysgeneraattorin itseherääminen, harmoninen resonanssi muuntajakytkennöissä, rinnakkaisresonanssi vierekkäisen voimajohdon yhteydessä ja ferroresonanssi ja tätä seuraava rinnakkaisresonanssi.

Väitöskirjan tulokset osoittavat, että tietokonesimuloinnit eivät yksin riitä epävarmuuksien tunnistamiseen. Siksi käytönpalautuksen suunnitteluun tulee sisältyä myös kenttäkokeita. Pimeäkäynnistysgeneraattorin testaaminen kenttäkokeilla ei riitä. Tämän lisäksi myös käytönpalautuksen alkuvaiheessa käytettävän sähkönsiirtoverkon käytönpalautus tulee testata. Tämä siirtoverkko mahdollistaa kulutuksen ja muun sähköntuotannon yhdistämisen pimeäkäynnistysgeneraattoriin.

Tulokset osoittavat myös, että normaaliin käyttöön laaditut simulointimallit eivät sovellu käytönpalautuksen suunnitteluun sähkövoimajärjestelmän erilaisesta käyttäytymisestä johtuen. Siksi järjestelmän käyttäytyminen kenttäkokeiden ja todellisen käytönpalautuksen aikana tulee rekisteröidä riittävän tarkoilla mittauksilla, jotta simulointimalleja voidaan muokata käytönpalautuksen suunnitteluun sopiviksi.

Käytönpalautuksen toimintamallit voivat olla epätavanomaisia ja hyvin erilaisia kuin sähkövoimajärjestelmän normaali käyttö. Siksi toimintamallit tulee suunnitella ennakkoon, todentaa kenttäkokeilla ja kouluttaa säännöllisesti käyttöhenkilöstölle.

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ABBREVIATIONS

AVR	Automatic voltage regulator
CIGRE	Conseil International des Grands Réseaux Electriques
DTS	Dispatcher training simulator
EMS	Energy management system
EMT	Electromagnetic transient
HILP	High impact low probability
HVDC	High-voltage direct current
IEA	International Energy Agency
IEEE	The Institute of Electrical and Electronics Engineers
NERC	North American Electric Reliability Corporation
OLTC	On-load tap changer
OTS	Operator training simulator
PMU	Phasor measurement unit
SCADA	Supervisory control and data acquisition
TFR	Transient fault recorder
TSO	Transmission system operator
UEL	Under-excitation limiter

LIST OF SYMBOLS

a, b, c	Phases a, b and c of a three-phase system
C	Capacitance
$\underline{E}_\mathrm{f}$	Generator internal electromotive force
$\vec{F}_\mathrm{a}$	Vector of magnetomotive force of the stator
$\vec{F}_\mathrm{f}$	Vector of magnetomotive force of the rotor
$\vec{F}_\mathrm{R}$	Resultant vector of $\vec{F}_\mathrm{a}$ and $\vec{F}_\mathrm{f}$
f_res	System resonance frequency
$\underline{I}$	Circuit current phasor
i_Y1a, i_Y1b, i_Y1c	Shunt reactor currents for wye Y1, phases a, b and c
i_Y2a, i_Y2b, i_Y2c	Shunt reactor currents for wye Y2, phases a, b and c
L	Inductance
L_Y1a, L_Y1b, L_Y1c	Shunt reactor inductances for wye Y1, phases a, b and c
L_Y2a, L_Y2b, L_Y2c	Shunt reactor inductances for wye Y2, phases a, b and c
Q_CTL	Capacitive reactive power of transmission network segment
Q_LS	Inductive reactive power of shunt compensation
R	Resistance
$\underline{V}_\mathrm{src}$	Voltage source voltage phasor
$\underline{V}_\mathrm{t}$	Generator terminal voltage phasor
X_C	Reactance of capacitance C
X_d	Generator direct-axis synchronous reactance
X_L	Reactance of inductance L
Y1	Wye Y1 of a double wye shunt reactor
Y2	Wye Y2 of a double wye shunt reactor

ORIGINAL PUBLICATIONS

Publication I	**Nikkilä A.-J.**, Kuusela A., Weixelbraun M., Haarla L., Laasonen M., Pahkin A., Fast restoration of a critical remote load area using a gradual voltage build-up procedure. *IET Generation, Transmission & Distribution*, Vol. 14, Issue 7, April 2020, pp. 1320-1328
Publication II	**Nikkilä A.-J.**, Kuusela A., Laasonen M., Haarla L., Pahkin A., Self-Excitation of a Synchronous Generator During Power System Restoration. *IEEE Transactions on Power Systems*, Vol. 34, Issue 5, September 2019, pp. 3902-3911
Publication III	**Nikkilä A.-J.**, Kuusela A., Harjula A., Rauhala T., Haarla L., Ferroresonance and subsequent sustained parallel resonance occurrence during power system restoration: analyses for system operation. *CIGRE Science & Engineering*, Vol. 21, June 2021, pp. 70-92
Publication IV	**Nikkilä A.-J.**, Kuusela A., Rauhala T., Pahkin A., Developing practices for power system restoration: The Finnish experience on restoration field-testing and training. *CIGRE e-Session (substituted the original Paris 2020 Session)*, virtual conference, 2020, paper C2-108, 11 p.
Publication V	**Nikkilä A.-J.**, Turunen J., Seppänen J., Haarla L., Experiences of analysing seasonal oscillatory properties of the Nordic power system using large data sets. *CIGRE Symposium: Experiencing The Future Power System…Today*, Dublin, Ireland, May 29-June 2, 2017, paper 051, 9 p.

1 INTRODUCTION

1.1 Background and Motivation

The power system restoration problem is practically as old as the electric system itself [1]. Modern societies have become increasingly dependent on reliable electricity, therefore major disturbances in the power system have significant impact on both society and economy. Thus, disturbances should be resolved as quickly as possible. If a blackout occurs, the utilities responsible for the operation of the power system should restore the system back to normal operation as soon as possible using power system restoration processes. Fast and robust processes are important for successful system restoration [2] and to limit the adverse impacts of blackouts [3].

Blackout occurrence is unpredictable [2] and blackouts affecting large geographical regions or even entire power system are rare. Today, many power systems are planned and operated using an N−1 principle [4] which means that the power system should withstand any single fault, including the most severe faults, determined by the system planning criteria.

Although system level blackouts are rare, the risk of a blackout occurrence cannot be ignored in system operation [5–9]. For example, extraordinary events outside the power system planning and operation criteria may lead the system to operate beyond its operational security limits [4]. Such high impact low probability (HILP) events are typically unpredictable chains of events with very low probability. However, if such a chain of events occurs, it will have high impact on the security of electric supply. [9]

The complexity of power systems has also increased, which may increase the occurrence of unpredictable chains of events and system restoration processes [3]. For example, converter-connected renewable energy sources and high-voltage direct current (HVDC) interconnections change the power systems. Therefore, it is important that the processes and methodologies for the system restoration planning properly identify and address the possible system restoration issues that may emerge as the power system changes.

Table 1 summarizes some examples of blackouts and their restoration times presented in the literature [5–8, 10–14]. Blackouts are typically caused by a sequence of unexpected events leading to a partial or full system collapse [5–9]. Therefore, power system restoration procedures are also a measure to prepare for extraordinary events outside the power system planning criteria.

Table 1. Some examples of blackouts occurred during the last decades.

Year	Description
1965	An unintentional trip of a backup protection relay caused a blackout in the Northeast Unites Stated power system affecting 30 million people. The system restoration took 13 hours. [6]
1977	The blackout in New York affected 8 million people. The system restoration took 25 hours. There were several reasons for this blackout, such as equipment malfunction, operating errors and insufficient preparation for emergency situations. [6]
1987	The blackout in Tokyo affected 3 million people. The major reason contributing the blackout was unusual high peak demand due to exceptionally hot weather leading to increased system loading and voltage instability. The system was recovered in 90 minutes. [6]
1996	A cascaded failure in the Western American power system led to the interruption of 2000 MW consumption. However, the system operations managed to prevent further disruptions by dividing the subsystems into islands using controlled and uncontrolled load shedding. [6]
2003	The US-Canadian system experienced a blackout due to voltage collapse affecting 50 million people in 2003. Several reasons have been identified as the causes of the blackout, such as insufficient reactive power resources and situational awareness. There were several triggers for the chain of events leading to the blackout such as a trip of a synchronous generator voltage regulator due to over-excitation and ground faults due to tree contacts because of insufficient vegetation management. The full system restoration took days. [6, 7, 10–12]
2003	The blackout in southern Sweden was triggered by two independent faults. First, a large generator tripped due to a fault and disconnected and after a 5-minute period a disconnector failed leading to two busbar faults and loss of another large generator. In total, 4 million people were affected in Sweden and Denmark. [6, 7, 13] The system was restored in hours.
2003	The Italian power system experienced a nationwide blackout in 2003. The trigger for the blackout was large power transfer in the system which caused conductor heating, increased line sag and consequent ground faults. Due to the large power transfer, the voltage phase angle difference over a transmission line was large and the re-closing of the line was unsuccessful. This led to further cascading disturbance until the Italian system disconnected from the European system and collapsed. The blackout occurred at 3 am and the electricity was restored to the large parts of the country during the same day. [6, 14, 15]
2006	The blackout in the Central European system affected 15 million people. Several reasons were identified as the causes for the blackout. In this case, the sequence of events leading to the disturbance was triggered the change in a scheduled outage. However, the outage planning was not comprehensively performed in the new situation. When the transmission line was disconnected, parallel transmission lines were overloaded leading to cascading events in the meshed transmission network. [16]
2007	In Victoria, Australia, bushfires caused a blackout of 2150 MW consumption affecting 0.5 million people. The restoration of the blackout took 4.5 hours. [6]
2018	An earthquake in Hokkaido area caused a blackout affecting the consumption of approximately 3000 MW. The earthquake caused generation disconnection due to vibrations. Also, several transmission lines were experiencing ground faults due to the vibrations. The restoration took about 45 hours [5]

Power system restoration is a complex task. After a blackout, the system being operated during the restoration is different to the system during the normal operation. Therefore, system operators are likely to encounter technical issues seldom encountered during normal system operation. In addition, there is not much time for the decision-making and the pressure to proceed quickly with the restoration may be significant. Thus, it is important that the operators in the control centers have planned and validated procedures to resolve the emergencies. [17–28]

The technical issues during system restoration cover aspects such as managing overvoltages and reactive power balances, harmonic resonances and switching transients, frequency and active power balance management and time-consuming switching operations. These issues are widely discussed in the literature. [17–28]

During the last decades, the power engineering industry had established several task forces and working groups to address system restoration issues. For example, The Institute of Electrical and Electronics Engineers (IEEE) task forces have published reports addressing the power system restoration issues already in the 1980s [1, 20]. Similarly, CIGRE working groups have addressed system restoration issues and published technical brochures in 2015 [3] and 2017 [19]. In addition, task forces or investigation committees, established by regulatory organizations, transmission system operators (TSOs) or governments have published reports after blackouts, for example: [10, 11, 15, 16].

Although significant efforts to enhance system restoration processes have been made, yet it is recognized that more information and best practices related to power system restoration should be shared [3]. For example, CIGRE technical brochure 608 [3] published in 2015 states that "in the disturbance reports publicly available, there does not appear to be any detailed description on the restoration process". In addition, the North American 2003 blackout task force concluded the need to evaluate and disseminate the lessons learned during system restoration [11]. Similarly, North American Electric Reliability Corporation (NERC) concluded the need to evaluate lessons learned during system restoration and the need to improve system modeling practices [10]. Also, inadequate understanding about the power system itself has been identified a critical factor affecting system restoration [31] by International Energy Agency (IEA) in 2005. Therefore, there is still room to further study the uncertainties related to the system restoration and methods and measures to manage the uncertainties when planning the restoration actions and restoring the system from a blackout.

The legislation has also developed to consider system restoration requirements [29, 30]. For example, the European legislation [29] requires that TSOs have power system restoration plans for both top-down and bottom-up restoration. In this thesis, top-down restoration refers to the restoration from high voltage transmission networks (for example, a neighboring power system or a large electrical island) towards regional transmission and distribution networks [19, 29, 32, 33] and bottom-up restoration refers to the use of the internal black-start resources of the power system for restoration towards high voltage transmission networks [19, 29, 32, 33]. In addition to the European legislation, NERC has also established requirements [30] related to power system restoration.

The motivation of this thesis initiated when the Finnish transmission network restoration practices were enhanced to consider the new requirements of the European legislation [29]. Furthermore, unexpected incidents during restoration field-tests raised the interest to study the uncertainties related to the restoration. Also, the changes in the power system affect restoration as the conventional generation is being replaced by distributed renewable generation. Special attention was given to the preparedness for a system level blackout. In this scenario, the entire synchronous area is in a blackout and the neighboring systems may not be used for the system restoration.

In the mentioned scenario, the restoration needs to be performed using a bottom-up procedure using resources located within the power system [19, 32]. During the bottom-up restoration, there are usually only few generators connected to the grid. Therefore, the short circuit current levels of the system might be very low. In other words, the system is extremely weak compared to the normal system operation.

As described in the literature, the weak network conditions may make the system prone to electrical phenomena seldom encountered during normal system operation such as synchronous generator self-excitation and resonance conditions. These electrical phenomena and related uncertainties are related to the voltage management and electrical resonances of transmission network during the early stages of the restoration. In addition, the exceptional voltages and operational procedures during transmission network restoration may cause issues with substation protection and automation systems, which should be considered in order to ensure fast and robust system restoration.

Based on the aspects discussed earlier, a need arose to further study the processes and methodologies for the planning and execution of the initial transmission network restoration during bottom-up restoration. The initial transmission network restoration refers to the early stages of the bottom-up power system restoration where the critical parts of the transmission network are being restored into service (energized). The purpose of the restored initial transmission network is to enable the connection of consumption and other generation together and consequently enable the further restoration of the remaining power system. In some papers, the transmission networks between the black-start generator and the other generation to be connected are referred to cranking paths [12, 24, 30].

In addition, there was a need to ensure that the technical uncertainties and their implications related to the system restoration are properly identified during the restoration planning process. Furthermore, there was a need to study how to manage the identified uncertainties when planning the restoration and restoring the system from a blackout. Also, there was a need to study how the procedures related to the management of the uncertainties should be trained for the operational personnel.

This thesis proposes a method of identifying technical uncertainties and their impact on the planning and execution of transmission network restoration. This thesis also develops means and measures to ensure that restoration planning identifies the technical uncertainties and mitigates their impact to enable fast and robust restoration. Furthermore, the thesis develops means and measures for real-time operations to manage the identified technical uncertainties when restoring the system from a blackout. Also, the thesis presents aspects for developing control center tools for supporting system restoration.

1.2 Scope and Objectives

1.2.1 Scope

Figure 1 illustrates the scope of the thesis. The thesis focuses on the black-start and initial transmission network restoration using bottom-up restoration in case of a system level blackout. The thesis studies the technical uncertainties related to the planning and execution of the restoration procedures. Other aspects such as consumption restoration, frequency and power balance management and island synchronization are out of the scope of this thesis.

The thesis focuses on transmission networks with nominal voltages that are high enough to trigger the electrical phenomena during switching procedures. In this thesis, the nominal voltage of the studied transmission network is 400 kV.

The thesis addresses initial transmission network restoration where a synchronous generator is used as a black-start resource. Other types of black-start resources such as HVDC systems and renewable energy sources are out of the scope of this thesis.

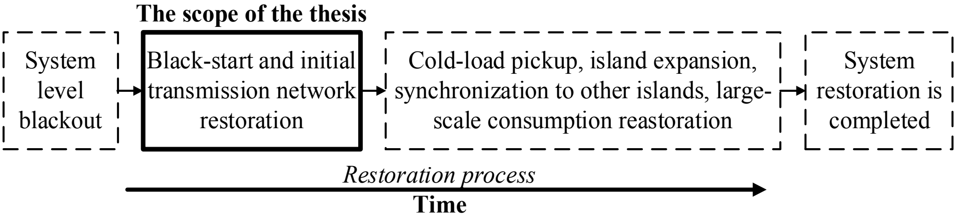


Figure 1. The scope of the thesis is on the black-start and initial transmission network restoration after a system level blackout. Consumption restoration, frequency and power balance management, island expansion and synchronization are out of the scope of the thesis.

1.2.2 Terminology

This thesis uses the following terminology.

Initial transmission network restoration refers to the black-start and the immediately following restoration phases. That is the energization of the selected network segment and its restoration into service, which then allows the connection of consumption and other generation. Connecting consumption and other generation are not included in this initial process.

Power system restoration refers to the restoration process of an entire power system from a blackout back to the normal system operation.

Uncertainties refer to the uncertainties related to electrical phenomena and protection and automation systems during initial transmission network restoration. The uncertainties are related to the factors, mechanisms and implications which are not fully well known and thus may compromise fast and robust system restoration. The uncertainties are seldom encountered during normal system operation but may emerge in extremely weak transmission networks inherent to the early stages of system restoration. The uncertainties may appear when analyzing and planning restoration, performing restoration field-tests and restoring the system from a blackout.

1.2.3 Objectives

The thesis has three research objectives.

Research objective 1 is to propose methods of identifying the technical uncertainties for system restoration and their impact on restoration planning and execution. In addition, the thesis aims at discussing the role of restoration processes as a part of preparation for the unexpected events in normal power system operation.

Research objective 2 is to develop means and measures to enhance restoration planning to identify the technical uncertainties and mitigate their impact. The thesis aims to develop a restoration planning process that enhances the identification and management of the technical uncertainties.

Research objective 3 is to develop means and measures to manage the identified technical uncertainties when restoring a power system after a blackout. The thesis aims to propose operative actions to manage the technical uncertainties during restoration plan execution. In addition, the thesis proposes requirements for the control center tools and restoration training processes.

1.3 Materials and Methods

This thesis uses two types of materials and methods: 1) electromagnetic transient (EMT) simulations with EMT models and 2) measurement data from the restoration field-tests performed in the Finnish 400 kV transmission network.

EMT simulation models and simulations were used to model and study the electrical phenomena. In addition, the EMT simulations were used to plan the restoration procedures and the field-tests.

EMT simulations enabled the analyses of the detailed voltage and current waveforms during the studied phenomena. In addition, the EMT simulations made it possible to calculate the harmonic resonance frequencies of the power system.

Field-test in the Finnish 400 kV transmission network were performed to test and validate the system restoration procedures. The measurement data from the field-tests were used to study the encountered uncertainties related to electrical phenomena and protection and automation systems and revise and validate the simulation models. Since the field-tests reflected the operational procedures during possible actual system restoration, the measurement data enabled to calibrate the simulation models specifically for the system restoration. Measurements during the field-tests comprise three types of measurements: conventional supervisory control and data acquisition (SCADA) measurements, phasor measurements unit (PMU) data and transient fault recorder (TFR) data.

PMU data made it possible to study the voltage and current phasors with sampling resolution of 50 Hz. The nominal frequency of the system was 50 Hz. Therefore, the PMU data included a sample per each cycle. The high resolution (in range of kHz) TFR data made it possible to study the detailed voltage and current waveforms measured at the substations and validate the EMT simulation models. SCADA measurements made it possible to obtain the data about the overall status of the transmission network which was essential when the incidents encountered during the field-tests were replicated in the simulations.

1.4 Thesis Outline

1.4.1 Publications

The thesis consists of the following five publications listed in the Original Publications Section.

Publication I analyzes harmonic resonances and switching transients using simulations and field-test data. The publication presents a *gradual voltage build-up procedure* for the soft energization of large transmission network segments comprising hundreds of kilometers of 400 kV transmission lines and several power transformers. The paper shows that the procedure makes it possible to restore the transmission network segment in a situation where the uncertainties related to identified 2nd and 3rd harmonic resonances were proven to present major risk with the conventional energization approach and prevent system restoration.

Publication II analyzes unexpected synchronous generator self-excitation encountered during system restoration field-tests. The analyses are performed using simulations and field-test measurement data. The self-excitation was triggered by the unexpected trip of an inductive shunt reactor. The reactor was tripped by a compensated reactor unbalance relay which had been parameterized with an approach suitable for normal system operation. However, the exceptional voltages during the restoration procedures caused the unexpected relay action and the trip of the reactor consequently triggering the self-excitation. The self-excitation caused an uncontrolled voltage-rise and prevented the system restoration. The paper shows the uncertainties of modeling self-excitation in EMT simulations.

Publication III analyzes *ferroresonance and subsequent sustained parallel resonance*, which both occurred during restoration field-tests. The paper also analyzes the uncertainties that these phenomena may cause for the restoration process. The analyses are performed using simulations and measurements. The paper focuses on a situation where a large transmission network segment with a power transformer is being energized but the energization is unsuccessful and the segment becomes disconnected, for example, due to relay protection maloperation. The paper shows that ferroresonance and subsequent sustained parallel resonance may cause dangerous overvoltages. The paper presents measures to mitigate the risk of resonance occurrence.

Publication IV presents practical experiences from the restoration tests in the Finnish transmission network and the lessons learned. The paper shows how the uncertainties may delay the execution of restoration field-tests. The paper also discusses how the control center tools and operator training should be enhanced to consider the requirements related to system restoration. In addition, the paper discusses the challenges of the intentional islanding restoration concept considered in the Finnish system as an alternative for black-start based restoration.

Publication V analyzes the variations in electromechanical oscillations in the Nordic power system during the normal system operation. The oscillations vary both daily and seasonally. The paper highlights the importance of maintaining adequate understanding about the system behavior and the importance of the preparedness for unexpected system level uncertainties.

1.4.2 Author's contribution

Publication I: Fast restoration of a critical remote load area using a gradual voltage build-up procedure

The author had the main responsibility for planning the field-tests and their measurements and applying the proposed gradual volage build-up restoration procedure for the Finnish power system restoration tests. The author had the main responsibility for the analyses and writing the manuscript. Co-authors assisted in the analysis, test arrangements and provided text to the certain sections of the manuscript. Dr. Michael Weixelbraun was responsible for the tests in the Austrian system and provided the text and figures from the Austrian tests. In addition, co-authors commented on the manuscript and improved the manuscript during the peer-review process.

Publication II: Self-Excitation of a Synchronous Generator During Power System Restoration

The author had the main responsibility for modeling, simulating and analyzing the self-excitation incident presented in the paper. In addition, the author had the main responsibility for the planning of the field-tests and measurement arrangements during the tests. Also, the author had the main responsibility for writing the manuscript. Co-authors assisted in the planning and execution of the field-tests. Co-authors also assisted in the analysis of the results. In addition, co-authors provided text and figures for the certain sections of the manuscript, commented on the manuscript and improved the manuscript during the peer-review process.

Publication III: Ferroresonance and subsequent sustained parallel resonance occurrence during power system restoration: analyses for system operation

The author had the main responsibility for modeling, simulating and analyzing the resonance incident presented in the paper. In addition, the author had the main responsibility for the planning and preparation of the field-tests and measurement during the tests. Also, the author had the main responsibility for the analyses and writing of the manuscript. Co-authors assisted in the analysis, test arrangements, provided text to certain sections of the manuscript and commented on the manuscript. In addition, co-authors improved the manuscript during the peer-review process.

Publication IV: Developing practices for power system restoration: The Finnish experience on restoration field-testing and training

The author had the main responsibility of planning the restoration field-tests and gathering and analyzing the lessons learned from the tests. Also, the author had the main responsibility for analyzing the feasibility of the intentional islanding restoration concept in the Finnish power system. The author had the main responsibility for writing the manuscript. Co-authors assisted in the analysis, provided text for certain sections of the manuscript as well as comments to the manuscript and improved the manuscript during the peer-review process.

Publication V: Experiences of analysing seasonal oscillatory properties of the Nordic power system using large data sets

The author had the main responsibility for performing the analysis of the electromechanical oscillations and their seasonal variations in the Nordic power system. The author had the main responsibility for the analyses and writing the manuscript. Co-authors assisted in the analysis and provided text for certain sections. In addition, co-authors commented on the manuscript and improved the manuscript during the peer-review process.

1.4.3 Thesis Structure

Chapters 1–3 present the literature review of the thesis. Chapter 1 presents the introduction. Chapter 2 presents the literature review of the power system restoration framework including restoration objectives and planning methodologies. Chapter 3 presents the literature review of technical uncertainties related to the transmission network restoration.

Chapters 4–6 present the results of the thesis. Chapter 4 presents the encountered technical uncertainties and proposes the methods of identifying the uncertainties and their impacts. Chapter 5 focuses on the restoration planning perspective. Chapter 5 proposes a procedure for planning the initial transmission network restoration and presents means and measures mitigate the encountered uncertainties when planning restoration actions. Chapter 6 focuses on the real-time system operations perspective. Chapter 6 presents the means and measures for real-time system operations to manage the identified technical uncertainties when restoring the system from a blackout. Chapter 6 also discusses the aspects related to the implementation of the restoration procedures in system operations.

Chapter 7 discusses the results and presents recommendations for the future work. Chapter 8 presents the conclusions of the thesis.

1.5 Contribution of the Thesis

The thesis includes three main contributions.

The first contribution answers **Research Objective 1** and proposes methods for identifying the technical uncertainties of system restoration planning and execution and the impact of the uncertainties. The contribution presented in Chapter 4 has been established based on the following main elements:

- The thesis shows that simulations alone are not sufficient for restoration planning. Instead, restoration field-tests with accurate measurements are required to validate the restoration plan and to enhance the simulation models (**I–IV**).
- The thesis shows that simulation models tuned for normal system operation are not sufficient for restoration studies (**I–IV**).
- The thesis analyzes and quantifies the impact of four electrical phenomena which were significant enough to prevent transmission network restoration during the first field-tests: harmonic resonance and switching transients (**I**), synchronous generator self-excitation (**II**), parallel line resonance (**III**, **IV**) and ferroresonance and subsequent sustained parallel resonance (**III**). Furthermore, the thesis identifies uncertainties related to protection and automation systems that prevented system restoration during field-tests (**II**, **IV**).

The second contribution answers **Research Objective 2** and develops means and measures to enhance restoration planning to identify and manage the technical uncertainties and mitigate their impacts on the restoration. The following are the main elements of the contribution presented in Chapter 5:

- The thesis shows the indispensable role of transmission network level restoration field-tests as a part of the restoration planning process (**I–IV**). In addition, the thesis shows the importance of the adequate understanding about the overall system dynamics (**I–V**) and weak network conditions (**I–IV)**.
- The thesis proposes an enhanced iterative restoration planning procedure which contains systematic transmission network level field-tests for 1) the validation of restoration actions and simulation models for restoration studies and 2) the training of operational personnel (**I**–**IV**).
- The thesis proposes measures to mitigate the impact of the identified uncertainties when planning restoration actions (**I**–**IV**).
- Since the uncertainties are seldom reported in the literature, the field-tests analyzed in the thesis may serve as valuable reference for the restoration planning in other power systems (**I–IV**).

The third contribution answers **Research Objective 3** and develops means and measures to manage the uncertainties of electrical phenomena and protection and automation systems when restoring a power system after a blackout. The following are the main elements of the contribution presented in Chapter 6:

- The thesis proposes operative actions to manage synchronous generator self-excitation (**II**), harmonic resonance and switching transients (**I**) and ferroresonance and subsequent sustained parallel resonance (**III**) when restoring the system from a blackout.
- The thesis shows that automation may significantly enhance the execution of restoration plans. Again, also the testing of automation processes is crucial (**IV**).
- None of the reported uncertainties (**I–V**) was observed using conventional SCADA measurements. Therefore, advanced measurements such as PMUs and TFRs should be available at the control centers. However, the operational personnel should be properly trained for using the measurements.

2 POWER SYSTEM RESTORATION FRAMEWORK

This chapter continues the literature review in Chapter 1 and presents the power system restoration framework. First, the chapter discusses the nature of the restoration problem and presents typical restoration strategies. After that, the chapter introduces the common objectives and tasks of system restoration. Finally, the chapter introduces the methods for system restoration planning and implementation.

2.1 Restoration Problem

Power system restoration refers to restorative procedures which are executed to return the system to the normal operation after an emergency such as a blackout [32–36]. Each power system has system specific characteristics that should be considered when planning restoration. Therefore, the identification and the sufficient consideration of all relevant aspects in the specific power system restoration makes both power system restoration and the planning of restoration actions challenging tasks. [19–23]

Power system restoration differs significantly from the normal system operation. Firstly, system level blackouts are rare which means that restoration processes are seldom executed in practice. In addition, the issues encountered during the restoration are highly unusual in normal system operation. Furthermore, while the normal system operation is highly automated with established processes, the system restoration involves manual and unconventional operational procedures under exceptional circumstances. [21]

The power system restoration problem is mathematically characterized as a non-linear optimization problem with multiple stages and objectives [34]. Moreover, the blackouts are typically related to the unexpected chains of events and the specific circumstances during the blackout are unknown when planning restoration. This causes uncertainty for both planning system restoration and restoring the system after a blackout. [5–9] Consequently, identifying and managing the relevant uncertainties related to the system restoration is critical [7, 9, 19–23].

In addition to the technical performance of the power system itself, there are a variety of other issues that may emerge during blackouts and restoration actions. For example, excessive alarms in SCADA and energy management systems (EMS) may be a significant issue during restoration and deteriorate situational awareness [24]. Also, possible communication system issues and the issues related to the logistics and the availability of critical personnel should be considered. [21, 12]

2.2 Restoration Strategies

There are two main power system restoration strategies: top-down restoration and bottom-up restoration [19, 29, 32, 33]. In addition, these strategies may be used simultaneously as a hybrid strategy [33]. Also, intentional islanding may be used to form an automatically disconnected islands with sufficient generation and load. The islands could then be used as starting points for the selected restoration strategy. [1].

Figure 2 presents a schematic diagram of the top-down strategy. In this strategy, the restoration starts from a strong voltage source such as a neighboring power system or a strong islanded system which, for example, has been intentionally disconnected from the power system just before the blackout. First, the sufficient high voltage transmission network is restored. After that, the restoration continues to the lower voltage transmission networks and distribution grids. [19, 29, 32, 33]

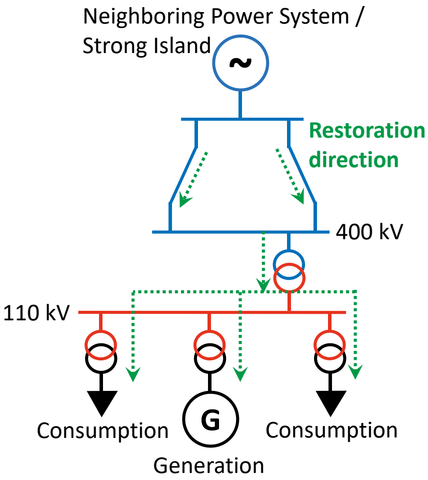


Figure 2. Schematic diagram of the top-down restoration strategy. The green arrows illustrate the direction of the restoration procedure. In the top-down strategy, the direction is from high voltage transmission networks towards lower voltage networks.

The advantage of the top-down strategy is that the strong voltage source makes it possible to directly restore a high voltage transmission network that typically covers large geographical areas including both generation and consumption. This reduces the need for complex and time-consuming restoration procedures required in weak systems and consequently expedites the restoration execution. [19] The disadvantage of the top-down strategy is that it requires a strong voltage source. If such is not available, the strategy is not possible.

Figure 3 presents a schematic diagram of bottom-up strategy which is in the focus of this thesis. The initial energy is provided by, for example, a black-start generator which performs the initial transmission network restoration. At this stage, the system is weak (i.e. the short circuit current level is very low). After that, the island is expanded by connecting local load and generation. When sufficient generation is connected to the island (i.e. the short circuit current level is sufficient), the restoration may proceed towards the high voltage transmission networks. [19, 32]

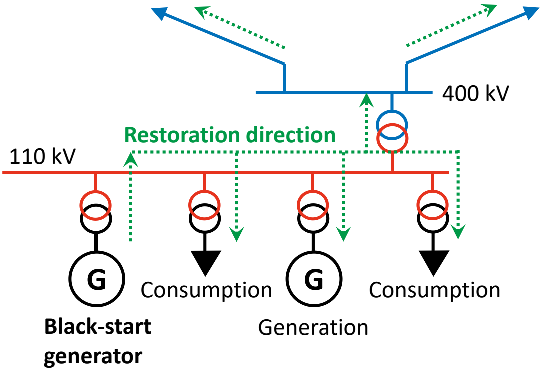


Figure 3. Schematic diagram of the bottom-up restoration strategy. The green arrows illustrate the direction of the restoration procedure. In the bottom-up strategy, the direction is from the black-start generator and local electricity grid towards the high voltage transmission networks.

The advantage of the bottom-up strategy is that it enables power system restoration also when the top-down restoration is not possible. The disadvantage is, however, that a black-start generator or other similar voltage source within the power system is required. [19, 32] In addition, the management of the extremely weak network may make the bottom-up restoration more complex and slower to execute than top-down strategy [17–19, 21, 23, 32].

2.3 Objectives and Tasks of Restoration

The overall objective of system restoration is to rebuild a stable electric system and restore consumption and generation as fast as possible [1, 21, 22, 35, 36]. When the system restoration begins, the root cause of the blackout is not necessarily known. Therefore, the restoration process should be suitable for various situations. The restoration process typically includes at least the following tasks [21]:

1. the determination of the system status after a blackout,
2. the preparation of black-start and other generators for the start-up,
3. the preparation of the transmission network and other relevant power grids for the energization,
4. the restoration of the selected transmission networks and power grids,
5. the formation of islanded power systems by connecting generation and consumption,
6. the reconnection of islands to each other.

The tasks can be executed sequentially or in parallel from different locations in the power system. [21]

2.4 Methods for Restoration Planning and Implementation

The power system restoration planning aims to develop a restoration plan that meets the restoration objectives of the specific power system and considers the system characteristics [21, 22, 26]. The methodologies for the entire system restoration planning and implementation have been presented in the literature [21, 22, 26].

Special attention should be given to fast and robust initial transmission network restoration since the restored network establishes the starting point for the remaining system restoration process. If the initial transmission network restoration fails, the restoration along the specific restoration path will not be able to proceed.

It appears that the analyses of the methodologies related to the planning and implementation of the early stages of the bottom-up restoration have received less attention in the literature. Especially, there are not many published studies, with validated simulation models and transmission network level field-tests, focusing on the uncertainties related to the planning of the initial transmission network restoration. Chapters 4–6 of this thesis analyze the uncertainties related to initial transmission network restoration and how to manage them when planning restoration and when restoring the system after a blackout.

Figure 4 presents typical steps for establishing a plan for entire power system restoration [21, 22, 26]. The process is iterative which means that each step may require multiple revision before the process is ready to proceed to the next step [26].

The restoration planning starts with defining the restoration objectives, selecting the strategy (i.e. bottom-up or top-down restoration) and identifying the relevant power system characteristics, such as the generation mix and control characteristics. [21, 26] In case of initial transmission network restoration, special attention should be given to generator start-up sequence and the energization of the initial transmission network making it possible to connect the black-start generator with other generation areas [19, 30, 32]. After that, the restoration sequences and relevant system characteristics are modelled in simulation tools and the models should be validated against the real power system data. [21, 26]

The planning continues by establishing the restoration guidelines. These describe the high-level principles of system restoration such as the principles to sectionalize the power system into black-start capable segments and the principles to resynchronize the restored segments into a larger power system. [21, 26]

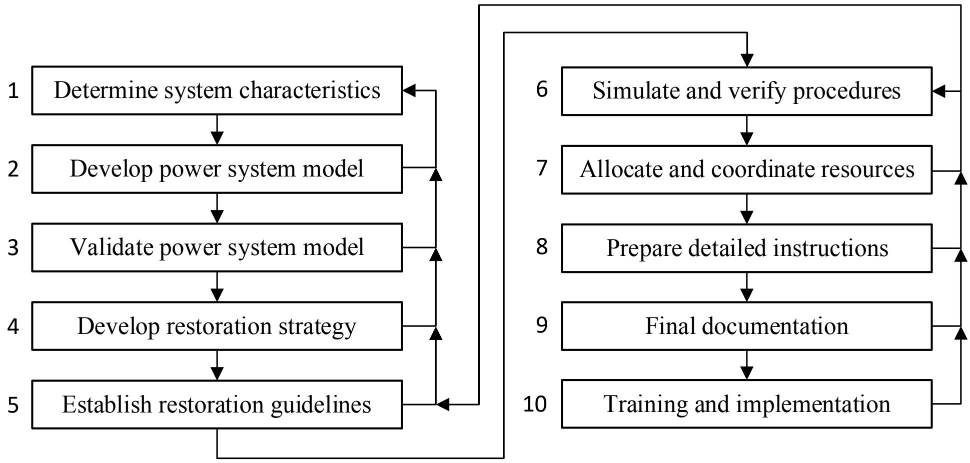


Figure 4. Typical steps for establishing a plan for entire power restoration. Modified from [26] Figure 2 based on [21] and [22].

Once the guidelines have been defined, the detailed restoration actions should be defined and verified. Since the full-scale restoration field-testing is practically impossible due to the impacts of a deliberate blackout, the simulation models have a significant role in the planning and validation of the restoration plans.

The verification of the restoration actions requires a variety of simulation tools. Power flow analyses study, for example, the reactive power balance, steady-state voltages and thermal loading of the transmission lines. In addition, time domain dynamic analyses are required to study, for example, frequency variations during load restoration and rotor-angle oscillations. Both EMT simulations are required to study switching transients and harmonic interaction during restoration and short circuit current calculations are needed to evaluate the relay protection performance. Furthermore, long-term dynamic simulations may be needed to study load restoration and the cold-load pickup effect. [17–19, 21, 23, 26, 32]

Finally, the resources required during restoration should be allocated and the detailed instructions should be prepared, documented and trained [21, 26]. Special attention should be given to the documentation format of the restoration plan so that it is easy to follow in case of an emergency. In addition, the technical reasoning behind the selected restoration strategies and guidelines should be documented. [21]

Dispatcher training simulators (DTS) or operator training simulators (OTS) have become an important tool for training dispatchers and controls center operators. A DTS/OTS makes it possible for operators to perform exercises on various emergency scenarios using the SCADA user interface and displays. [3, 34, 36–42] In addition, SCADA integrated machine learning and knowledge-based systems may also assist the operator in decision making during restoration execution [23, 43–50].

Since simulation models have a major role in restoration planning, it is essential that the models are properly validated to represents the phenomena of interest. [21, 26] For example, the analysis of North American 2003 blackout discovered that simulation models showed stable system operation while undamped oscillations were observed in the real system [6, 13].

Regulation and legislation such as [29, 30], specify mandatory and regular tests on black-start generators and its black-start function. Therefore, many TSOs perform such tests. However, the regulation and legislation, such as [29, 30], do not require transmission network restoration to be verified using field-tests. Also, simulations are considered as a feasible approach to planning and verifying the restoration procedures when practical testing in the transmission network is not possible [32]. However, some TSOs also perform field-tests to verify that black-start generators can restore the transmission network which may be used to supply start-up power for other generators that do not have the black-start functionality [19, 32].

The field-testing of transmission network equipment, such as 400 kV transmission line and transformer energization, may be challenging. Even the testing of a single transmission line and power transformer restoration may require complex test arrangements and may be difficult to organize in transmission networks. Thus, such test may significantly affect the system operation and even risk the operational security of large geographical areas. [19, 32]

This thesis and Publications I–IV show that if the validation of the restoration plans relies completely on simulation models and simulation models have not been validated against the relevant field-test data, the restoration procedures are subjected to significant uncertainties which may delay or even prevent system restoration using specific restoration paths. In case a blackout, the black-start itself may be likely successful especially if the black-start generator is regularly tested. However, the uncertainties related to the transmission network restoration may prevent the restoration of the initial transmission network which would establish the starting point for the restoration of the remaining power system. This thesis discusses in detail the identification of such uncertainties (Chapter 4), the management of the uncertainties when planning the restoration (Chapter 5) and the operational practices to manage the uncertainties when restoring the system from a blackout (Chapter 6).

3 LITERATURE REVIEW ON UNCERTAINTIES OF TRANSMISSION NETWORK RESTORATION

This chapter continues the literature review in Chapter 1 and Chapter 2 but concentrates on the uncertainties related to electrical phenomena and protection and automation systems during the initial transmission network restoration. First, the chapter reviews the electrical phenomena which the existing literature has identified to have a major impact on the restoration and therefore may compromise the fast and robust restoration. After that, based on the literature, the chapter reviews the uncertainties related to these phenomena. Finally, the chapter reviews the uncertainties related to protection and automation systems during restoration.

3.1 Electrical Phenomena Affecting Restoration

During the initial transmission network restoration, managing the system voltage is of especial concern [18, 51, 52]. Special attention should be given electrical phenomena causing overvoltages that may damage the grid equipment and delay or even prevent the system restoration using specific restoration paths. The occurrence of these phenomena is mainly due to a weak system caused by low short circuit current levels due to few connected generators, lightly loaded transmission lines, insufficient inductive shunt compensation and exceptionally low system resonance frequencies. [18, 51–58]

The following phenomena are commonly reported causing overvoltages in weak systems are therefore of a special interest of this thesis:

- switching transients and harmonic resonance [18, 51–56],
- sustained overvoltages [18, 51, 52, 54–56],
- parallel line resonance [57],
- ferroresonance [52, 55–57],
- synchronous generator self-excitation [51, 52, 54, 56, 58].

The possible triggers and implications related to the phenomena may compromise fast and robust restoration and therefore cause uncertainty for both restoration planning and restoring the system after a blackout. The theory of the mentioned phenomena is well presented in the literature [18, 51–58]. However, the phenomena are seldom encountered during normal system operation, or the phenomena may have different characteristics during restoration than normal operation.

Since blackouts and consequent restoration actions are rare, there are not many reports on the phenomena encountered at transmission networks, such as a 400 kV system, during actual system restoration. There are neither many reports nor studies on the phenomena encountered during restoration field-tests performed in practice in real transmission networks. Therefore, there are not much reference field-data regarding the practical implications and the triggering mechanisms of the phenomena during initial transmission network restoration although the presence of these phenomena during restoration is widely acknowledged by the literature.

Publications I–IV and this thesis provide a set of references showing both practical implications and theoretical analysis of the mentioned phenomena during initial transmission network restoration with simulations and field-test measurements. Prior to this thesis and the publications, systematic analyses combining data from transmission network level field-tests and simulation models validated based on the field-test data have received less attention in the literature. The thesis presents measures for the identification of the phenomena (Chapter 4) and management of the phenomena when planning restoration in advance (Chapter 5) and when restoring the system from a blackout in real-time (Chapter 6).

3.2 Uncertainties Related to Electrical Phenomena

3.2.1 Switching Transients and Harmonic Resonance

Poorly damped high frequency switching transients may cause overvoltages in weak transmission networks, damage the grid equipment during restoration and consequently compromise fast and robust system restoration. Such transients are typical concerns during the restoration of transmission networks with voltages over 100 kV [18]. The transients are mainly caused by the energization of capacitive elements such as non-loaded transmission lines. [18, 51–56]

Transformer energization in requires special attention during restoration since the transformer inrush current has significant harmonic contents. [54, 59] A transformer energization may cause high amplitude and long duration transients and consequent overvoltages in a weak system with poor damping. The transient is essentially caused by the magnetizing inrush current of the transformer core. In a weak system, the overvoltages may, in the worst case, overexcite the transformer and consequently lead to sustained or even escalating overvoltages [18, 51, 54–56].

The transient triggered by a transformer energization may even drive other, already connected transformers, into saturation and trigger sympathetic interaction between the transformers. Sympathetic interaction may significantly affect the duration and level of the transients. [59–63]

Harmonic resonance occurs when the natural resonance frequency of a power system coincides with a harmonic component excited in the system. In harmonic resonance, the damping of the system is poor and even small transients at the resonance frequencies may excite escalating overvoltages. [18, 51]

Harmonic resonance is especially a concern during system restoration. Since there are only few generators connected to the system (i.e. a weak system), Thevenin's equivalent inductance of the system may be significantly higher than during the normal system operation. Also, connecting capacitive elements to the system, such as transmission lines, tends to further decrease the resonance frequencies. Thus, the resonance frequencies of the power system may be exceptionally low. [59]

The relation between the system resonance frequency f_{res}, inductance L and capacitance C may be observed from Equation (1). Increasing L (for example, decreasing the system strength) or C (for example, connecting more transmission lines) will result in lower f_{res}.

$$f_{\mathrm{res}} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

If the system has a natural resonance frequency (or frequencies) close to the harmonics excited by transformer energization, the energization may lead to undamped transients and dangerous overvoltages [59]. Such overvoltages may compromise fast and robust system restoration. As Publication I shows, the resonance frequencies may vary significantly during the restoration. Therefore, it is important to consider the uncertainties related to harmonic resonance and the development of the network resonance frequencies during restoration.

Table 2 lists typical examples of techniques presented in the literature to mitigate transformer inrush currents and transient overvoltages caused by harmonic resonance. However, the techniques in Table 2 are not necessarily feasible during restoration. For example, Publication I presents a situation where the system has a harmonic resonance frequency near the second harmonic (100 Hz) and a transformer needs to be energized. In this situation, the de-tuning of the system resonance frequency by changing the topology (Table 2, Item 6) would not be possible. Also, there is not a generator which would enable the transformer soft energization (Table 2, Item 5).

Table 2. Examples of techniques presented in the literature to mitigate transformer inrush currents and transient overvoltages due to harmonic resonance.

1. Controlled switching [59] Controlling the closing times of the energizing circuit breaker phases may reduce the transformer inrush current compared to random three-phase closing. [59]
2. Pre-insertion resistors [59] Correctly designed pre-insertion resistors installed in series with the energizing circuit breaker may reduce the inrush current. [59]
3. Transformer on-load tap changer (OLTC) position adjustment [59, 64] Adjusting the transformer tap position before energization may reduce the transformer inrush current. [59, 64]
4. Reduction of system voltage [59] Reducing the system voltage before a transformer energization may reduce the inrush current [59].
5. Transformer soft energization using a generator [59] Slow and gradual transformer energization using a generator connected to the transformer makes it possible to avoid inrush current and harmonic resonance especially in a weak system during system restoration [59].
6. De-tuning of resonance frequencies [59] System resonance frequencies may be changed, if possible, by changing the system topology [59].
7. Increasing the system load [51, 59] Increasing the system load increases the damping of the transients [51, 59].
8. Reduction of source impedance with other generators [59] Connecting other generators to the system will reduce the source impedance of the system and result in higher resonance frequencies. [59]

The soft energization of a single transformer [59] may be extended to energize transmission lines and transformers connected to each other at the same time [65]. The concept has been briefly discussed in the literature [65]. However, there are not many descriptions of soft energization procedures for the restoration of geographically large transmission network segments comprising several transformers and hundreds of kilometers of transmission lines. Especially, there are hardly any studies focusing on the applicability of the procedures in situations where harmonic resonance prevents the conventional transformer energization.

Publication I and this thesis present a procedure for the soft energization of geographically large high voltage transmission network segments. The procedure is referred to *the gradual voltage build-up procedure*. Publication I and this thesis show that the procedure is applicable to the restoration of transmission lines and power transformers even when harmonic resonance prevents the conventional energization during initial transmission network restoration. Moreover, Publication I validates the applicability of the procedure with field-tests to restore transmission networks comprising several transformers and hundreds of kilometers of transmission lines.

3.2.2 Sustained Fundamental Frequency Overvoltages

Sustained fundamental frequency overvoltages have the same frequency as the power system itself. Such overvoltages are a typical concern in a weak transmission network during bottom-up restoration and may compromise fast and robust system restoration. Overvoltages may cause, for example, equipment damage, transformer heating, overexcitation and generate harmonic distortion causing other issues in the system [18, 51, 54–56].

According to the literature, such overvoltages are mainly caused by the capacitive charging currents of lightly loaded transmission lines [18, 51, 54–56]. The phenomenon is also referred to Ferranti effect [52]. Sustained overvoltages are managed by ensuring that sufficient inductive shunt compensation is connected to the system. Sources of inductive reactive power are, for example, shunt reactors and synchronous generators. [18, 51, 52, 54–56]

However, Publications II and III show that the Ferranti effect is not necessarily the only phenomenon causing sustained fundamental frequency overvoltages during system restoration. Therefore, managing only Ferranti effect is not sufficient to mitigate uncertainties related to sustained fundamental frequency overvoltages.

Publication II discusses the implications of synchronous generator self-excitation which may lead to significant fundamental frequency overvoltages. The self-excitation phenomenon itself is well-known. However, the phenomenon is rare and there are hardly any detailed assessments of recent restoration related self-excitation incidents applying both field-test data and EMT simulation results. The phenomenon is discussed more in Section 3.2.5.

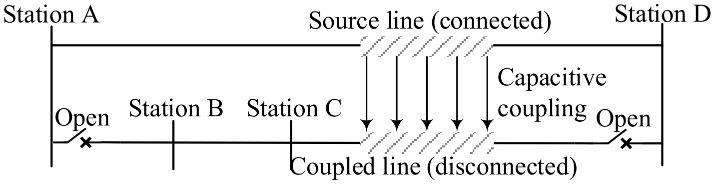
Publication III discusses the sustained fundamental frequency overvoltages excited by *the ferroresonance and subsequent sustained parallel resonance*. The phenomenon is related to both parallel line resonance and ferroresonance which are discussed in Sections 3.2.3 and 3.2.4.

3.2.3 Parallel Line Resonance

Parallel line resonance [57] refers to a situation, where the transmission line shunt capacitance is almost entirely shunt compensated using inductive shunt compensation. If the transmission line becomes disconnected, the natural resonance frequency of the segment is close to the system operating frequency [67, 68]. Figure 5 illustrates an example of parallel line resonance.

In this situation, high voltages may be easily induced to the disconnected segment due to, for example, capacitive coupling between the connected line (already restored into service) and the disconnected transmission network segment (being restored into service). These voltages may be unexpected during system restoration. [57]

During the early stages restoration, there may be one or only few generators connected to the system and their reactive power capability to support the system voltage may be small. Thus, connecting the transmission segments into service may require them to be almost entirely compensated using inductive shunt compensation to avoid overvoltages caused by exceeding the reactive power capability of the connected generators. Therefore, the shunt compensation should be connected to the segment before the segment is connected to the system creating the parallel resonance circuit to the disconnected (floating) transmission segment, which is waiting for restoration.



The shunt compensation level of the disconnected transmission system segment is close to 100 %

Figure 5. Schematic diagram of a topology causing a parallel line resonance. The transmission line between Station A and Station D is connected. The transmission segment consisting of three successive lines (Line A–B, Line B–C, and Line C–D) between Stations A and Station D is disconnected. The shunt capacitance of the transmission lines in the disconnected segment is almost 100 % shunt compensated. The dashed lines represent a common right-of-way where the transmission lines are capacitively coupled.

The possibility of parallel line resonance during restoration actions has been identified [57, 66] but the detailed assessment of the uncertainties related to the phenomenon applying both field-test measurement data and EMT simulation results appear to have received little attention in the literature. However, some analyses [67–

71] highlight the possibility of the dangerously high induced voltage due to resonant conditions during normal system operation.

Publications III and IV show that switching procedures during restoration may make the system prone to parallel line resonance and the resonance may delay restoration. Publication III discusses the measures to avoid the parallel line resonance and shows that the resonance may be triggered by a ferroresonance under specific circumstances which are further discussed in Section 3.2.4. Such chain of events is referred to *ferroresonance and subsequent sustained parallel resonance* in this thesis.

3.2.4 Ferroresonance

Ferroresonance is a phenomenon where a non-linear inductance, such as a ferromagnetic transformer core, is oscillating in and out of its magnetic saturation region. Ferroresonance requires that there is capacitance in the resonance circuit and an energy source that supplies the circuit losses and sustains the resonance. [72–76]

Ferroresonance incidents are divided into four categories depending on the voltage waveform during the resonance: periodic (subharmonic), fundamental frequency, quasi-periodic and chaotic modes. [57, 73–75] In the periodic ferroresonance mode, the waveforms are highly distorted and repeat themselves. The fundamental frequency ferroresonance mode is a type of periodic mode where the oscillation consists mainly the frequency of the source supplying the resonance circuit. In the quasi-periodic mode, the oscillations are non-periodic and comprise at least two main frequency components. The chaotic ferroresonance mode is characterized by irregular waveforms and unpredictable behavior. [57, 73–75]

Ferroresonance has been excited in numerous circuit configurations. Figure 6 presents a schematic ferroresonance circuit with non-linear inductance L (reactance X_L), capacitance C (reactance X_C) and resistance R presenting the circuit losses.

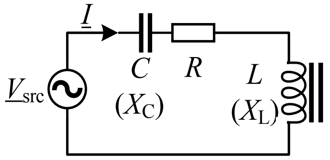


Figure 6. A schematic diagram of a ferroresonance circuit. C is the circuit capacitance (reactance X_C), R is the circuit resistance (losses) and L is the non-linear inductance (reactance X_L).

The detailed mathematical analysis of ferroresonance circuits is complex [72–76] and out of the scope of this thesis. However, ferroresonance characteristics of a circuit may be studied using fundamental frequency linear analysis by examining the circuit current ($\underline{I}$) and voltage ($\underline{V}_{\mathrm{src}}$) pairs that satisfies Equation (2). For simplification, the resistance of the circuit is neglected ($R = 0\ \Omega$). [72–76]

$$\underline{V}_{\mathrm{src}} = \underline{I}(\mathrm{j}X_{\mathrm{L}} - \mathrm{j}X_{\mathrm{C}}) \tag{2}$$

According to [72–76], the risk of ferroresonance occurrence may be examined by investigating the number and stability of the current-voltage pairs with different values of X_{L} (highly non-linear characteristics due to saturation) and X_{C}. Multiple stable current-voltage pairs indicate the circuit tendency for ferroresonance oscillations. However, the behavior of ferroresonance circuits is difficult to predict and the circuits are sensitive to initial conditions and circuit parameters. [72–76]

In power systems, ferroresonance may occur under many circumstances. For example, incidents are related to voltage transformers [57, 72–76] or power transformers [57, 72–76] have been reported. In addition, ferroresonance has been reported on a series compensated transmission line [77].

Many topologies prone to ferroresonance may seem unrealistic during normal system operation but may likely occur during restoration [52, 55–57]. Although ferroresonance is analyzed in the literature [78–84], there are not many reports on of ferroresonance incidents during bottom-up restoration or the analyses of uncertainties related to ferroresonance during restoration.

Power transformer ferroresonance is of special interest of this thesis as it might occur when switching large transmission network segments. Literature [78–81] reports ferroresonance incidents when a disconnected transmission line and a power transformer are connected to each other, and a connected transmission line is in parallel with the disconnected transmission line. Figure 7 presents a simplified and schematic diagram of this topology. In this topology, the ferroresonance circuit is established between the shunt capacitance of the transmission line and the power transformer. The parallel connected and capacitively coupled transmission line provides the energy for the circuit. [78–81]

Table 3 summarizes the measures to manage power transformer ferroresonance. However, the measures in Table 3 are not necessarily practical during system restoration. Many measures are related to avoiding topologies that make the system prone to ferroresonance. However, those topologies may be difficult to foresee and avoid during restoration.

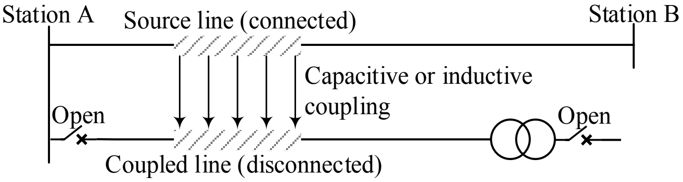


Figure 7. Schematic diagram of a topology where a disconnected transformer and transmission line in series have a parallel connected transmission line. The source line (connected) and the coupled line (disconnected) are capacitively or inductively coupled.

Publication III shows that under specific circumstances, a power transformer ferroresonance may lead to subsequent sustained parallel line resonance (i.e. *ferroresonance and subsequent sustained parallel resonance*). Such chains of events have not been reported and analyzed in the literature using simulation results and field-test data prior to Publication III and this thesis. Publication III also discusses measures to avoid *ferroresonance and subsequent sustained parallel resonance* during system restoration.

Table 3. Measures presented in the literature to prevent or mitigate the risk of power transformer ferroresonance occurrence.

1. Reduce the length of the disconnected transmission line connected to the transformer [57] Many ferroresonance incidents have occurred when a power transformer and transmission line have disconnected but left connected to each other. One measure to reduce the risk of ferroresonance is to minimize the allowed length of disconnected transmission line that may be left connected to the transformer. This essentially reduces the capacitance connected to the disconnected transformer. [57]
2. Increase the resonance circuit losses [57] Increasing the resonance circuit losses may reduce the risk of ferroresonance occurrence [57].
3. Enhance phase conductor transposition [57] This minimizes the energy transfer from parallel transmission lines to supply the resonance circuit [57].
4. Disconnect transformer from the transmission line as soon as possible [57, 74] If a resonance occurs the transformer is disconnected from the transmission line as soon as possible. [57, 74]
5. Transformer soft energization [57] A generator is used to energize the transformer gradually from zero to normal operating voltage. [57]

3.2.5 Synchronous Generator Self-Excitation

Synchronous generator self-excitation is a phenomenon encountered especially in weak systems if a synchronous generator becomes connected to a capacitive load. Self-excitation occurs when the capacitive load exceeds the generator reactive power capability. During restoration, such capacitive load may be, for example, a transmission line with insufficient inductive shunt compensation. Self-excitation leads to uncontrolled voltage-rise which may damage the grid equipment [85–95] and consequently delay or even prevent system restoration. Therefore, it is important to understand the uncertainties related to self-excitation during system restoration.

When a synchronous generator is connected to a purely capacitive load, the stator current $\underline{I}$ becomes purely capacitive (no active load). Consequently, the vector of the magnetomotive force of the stator ($\vec{F}_\mathrm{a}$) is aligned to the same direction as the vector of the magnetomotive force of the rotor ($\vec{F}_\mathrm{f}$). In other words, the magnetic field of the rotor and stator are at the same direction. In case of purely inductive load, the direction of $\vec{F}_\mathrm{a}$ (stator field) would have an opposite direction than the rotor magnetomotive force. The resultant magnetomotive force vector $\vec{F}_\mathrm{R}$ is: [92]

$$\vec{F}_\mathrm{R} = \vec{F}_\mathrm{a} + \vec{F}_\mathrm{f} \tag{3}$$

Figure 8 presents a schematic diagram of a synchronous generator connected to a purely capacitive load (reactance X_C). The relation between the stator current $\underline{I}$, generator terminal voltage $\underline{V}_\mathrm{t}$ and generator internal electromotive force $\underline{E}_\mathrm{f}$ is obtained from the following equations: [92]

$$\underline{I} = \frac{\underline{V}_\mathrm{t}}{X_\mathrm{C}} \tag{4}$$

$$\underline{E}_\mathrm{f} + \mathrm{j}\underline{I}X_\mathrm{d} = \underline{V}_\mathrm{t} \tag{5}$$

The excitation system supplies the generator field voltage and current which create the rotor field ($\vec{F}_\mathrm{f}$). The generator automatic voltage regulator (AVR) regulates the rotor field to maintain the generator terminal voltage $\underline{V}_\mathrm{t}$. [92]

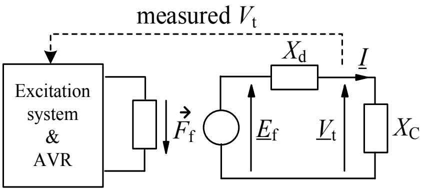


Figure 8. Schematic diagram of a synchronous generator connected to a purely capacitive load X_C. Generator AVR regulate the rotor field $\vec{F}_\mathrm{f}$ to maintain constant terminal voltage $\underline{V}_\mathrm{t}$. $\underline{E}_\mathrm{f}$ represents the internal electromotive force, $\underline{I}$ is the stator current and X_d is the direct-axis synchronous reactance of the generator. Modified from [92] Figure 3.12.

If the rotor field $\vec{F}_\mathrm{f}$ is constant and the purely capacitive stator current $\underline{I}$ increases, both the stator field ($\vec{F}_\mathrm{a}$) and, in consequence, the resultant field ($\vec{F}_\mathrm{R}$) increase. Thus, the AVR should decrease the rotor field ($\vec{F}_\mathrm{f}$) to maintain the constant generator terminal voltage $\underline{V}_t$. However, the rotor field has a minimum limit to ensure stable generator operation. When this limit is reached and the capacitive current of the stator increases, the generator loses the capability to control the terminal voltage. The situation results in uncontrolled voltage-rise. [92]

Not many papers analyze self-excitation and the management of related uncertainties during transmission network restoration. Especially, analyses of self-excitation incidents with validated simulation models and field-test measurements have received less attention in the literature.

Publication II analyzes a recent (2017) self-excitation incident that occurred during restoration field-tests. Publication II shows the challenges related to the modelling of excitation systems without having field-test measurements that could be used as a reference when simulating self-excitation. The publication shows how the under-excitation limiter (UEL) parameters of the excitation system affect voltage rise mitigation. Also, the publication shows the impact of the excitation system negative field current capability on voltage rise.

3.3 Uncertainties in Protection and Automation and Systems

3.3.1 Protection

The uncertainties caused by relay protection issues during system restoration have been discussed in the literature [96–100]. The power system changes as the restoration proceeds. Therefore, the protection and automation systems may be subjected operating actions seldom performed during normal power system operation. In addition, switching actions excite currents and voltages seldom encountered during normal system operation. Also, fault current levels may be exceptionally low. Consequently, the protection may not be able to clear faults during restoration if exceptionally low short circuit current levels are not properly considered in the relay settings or the protection systems may trigger undesired protection operations. The distribution system protection may also affect the system restoration especially if black-start resources are in the distribution grids. [96–100]

Addressing protection issues during restoration requires the consideration of the performance of various relay protection systems as illustrated by Table 4. However, the detailed analysis of the various functionalities is out of the scope of this thesis.

The protection issues related to the voltage management are of special concerns during the early phases of the transmission network restoration [97]. Since inductive shunt compensation seem to be critical for managing system voltages, as shown in Publication II, possible shunt compensation protection issues are of special interest of this thesis. However, the performance of inductive shunt compensation protection during restoration appears to have received less attention in the literature. Publication II and this thesis show that protection system issues may cause unexpected events during restoration. For example, inductive shunt compensation protection issues may trigger uncontrolled voltage rise due to black-start generator self-excitation. Chapter 4 and Chapter 5 discuss these issues in detail.

Table 4. Examples of protection and automation systems requiring special attention during system restoration.

1. Protection of transmission network and its components • Distance relays and reclosing schemes [1, 96] • Synchro-check relays [96] • Differential relays and their harmonic restraint [96] • Automatically switched capacitors [96] • Overvoltage and overcurrent relays [97] • System protection: intentional islanding, low frequency isolation [96]
2. Synchronous generators protection and control • Negative sequence voltage relays [96] • Out-of-step relays [1, 96] • Overexcitation relays [1, 96] • Under-excitation relays [1, 96, 97] • Loss of excitation relays [97] • Under-frequency relays [1, 96] • Excitation systems relays [1, 96, 97] • Black-start automation sequences [97]

In principle, the protection issues are managed by identifying possible problematic protection functions and enhancing the relay protection configuration to ensure that the protection performs correctly during restoration. [96–100] However, as discussed in Publication II and in this thesis, identifying possible problematic issues may be challenging due to the unconventional nature of the restoration actions.

As discussed in Publication II, although the protection has performed as expected during normal operation, the exceptional voltages during system restoration caused the compensated reactor unbalance protection to trip the dry-type reactor. This kind of relay is not typically listed as a protection function affecting system restoration.

Publication II and this thesis also show the importance for the correct operation of overvoltage protection during system restoration. Especially, the protection of the compensation devices themselves should be carefully planned considering both the protection of the compensation devices and the impact of the possible disconnection of a compensation device on other system equipment.

3.3.2 Automation and Protection of Black-Start Generator

Robust automation and start-up sequences for the black-start generator are critical during system restoration. In addition, the various protection and control systems of the generator and its excitation system may significantly affect the generator capability to manage the transmission network voltages during restoration. [97]

Black-start requires many procedures that may be significantly different from the normal generator operation. For example, black-start may require blocking of certain protection functions and executing dedicated start-up sequences. Therefore, special attention should be given to the testing of the procedures to ensure robust black-start. [97] Some legislation [29, 30] require regular tests on black-start generators.

This thesis and Publications I–IV show that testing only the black-start generator is not sufficient. The publications and this thesis show that the tests should also include initial transmission network restoration to ensure the identification of the uncertainties related to the automation and protection of the black-start generator. In addition, the testing of initial transmission network restoration is required to ensure proper coordination with black-start generator and transmission network protection and automation systems. Publication IV quantifies the significant delays that black-start generator automation issues may cause during restoration. Chapter 4 and Chapter 5 discuss these aspects in detail.

4 IDENTIFICATION OF UNCERTAINTIES

This chapter presents the results of the thesis but focuses on the identification of uncertainties related to the electrical phenomena and protection and automation systems. This chapter is based on Publications I–IV. First, the chapter introduces the flow of restoration planning activities which were performed to obtain the results presented in the publications. After that, the chapter presents the simulation and the field-test results of the electrical phenomena and the observations on protection and automation systems. Finally, the chapter proposes the methodologies for the identification of the uncertainties.

4.1 Introduction

The aim of the restoration planning process was to develop a fast and robust procedure for the restoration of a 400 kV transmission network segment illustrated in Figure 9. Once the segment would be restored into service, consumption and other generation could be connected to the segment and consequently the segment would establish a starting point for the remaining entire power system restoration.

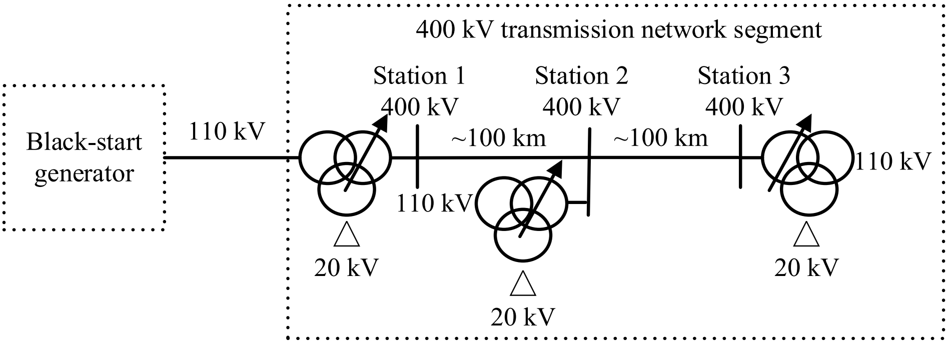


Figure 9. Schematic diagram of a black-start generator and the 400 kV transmission network segment for which the initial restoration procedure was developed in this thesis. The segment includes 400 kV transmission lines, three 400/110/20 kV transformers (400 MVA each), and inductive shunt reactors (~65 Mvar Δ). The transformer 110 kV at windings are disconnected from the remaining grid at Station 2 and Station 3.

Both simulations and restoration field-tests were performed during the development of the restoration procedure. Also, black-start generator automation sequences were enhanced to enable remotely controlled black-start and initial transmission network restoration without the need for local generator operations.

First, the analyses focused on harmonic resonance. As discussed in Section 4.2.1 and concluded by Publication I, the energization of the 400 MVA transformer at Station 3 (Figure 9) was not possible due to harmonic resonance and consequent overvoltages if the grid voltage is close to nominal value during energization. Therefore, a new procedure, *the gradual voltage build-up procedure*, was developed to enable the energization of the segment in Figure 9 despite the harmonic resonance. The new procedure is presented in Publication I.

When *the gradual voltage build-up procedure* was tested for the first time, erroneous tripping by a shunt reactor protection relay caused the self-excitation for the black-start generator. Publication II and Section 4.2.2 of this thesis discuss the uncertainties related to self-excitation modelling and the issues that self-excitation may cause for system restoration. Section 4.3.1 focuses on shunt reactor protection issues. The self-excitation prevented using *the gradual voltage build-up procedure*. Therefore, there was a need to better understand and solve the issues related to the shunt reactor protection and consequent generator self-excitation before *the gradual voltage build-up procedure* could be used for the segment restoration.

After Publications I and II, the analyses focused on possible issues, which may emerge when additional transmission lines and power transformers are connected to the already restored initial transmission network. Publication III and Section 4.2.3 focus on *ferroresonance and subsequent sustained parallel resonance*. The resonance occurred when a close to 100 % shunt compensated transmission network segment was connected to the system but became subsequently disconnected.

Publication IV shows that parallel line resonance significantly delayed the execution of the restoration field-tests. The mechanism of parallel line resonance is analyzed in Publication III and the results are discussed in Section 4.2.4.

Publication IV presents the issues related to the black-start generator automation systems encountered during the field-tests. These results are discussed in Section 4.3.2.

4.2 Simulation and Field-Test Results of Electrical Phenomena

4.2.1 Harmonic Resonance and Transformer Energization

Publication I shows that the energization of the 400 MVA transformer at Station 3 (Section 4.1, Figure 9) was not possible in the studied topology due to harmonic resonance. The harmonic resonance frequency of the system is close to the 2nd harmonic (100 Hz). Therefore, if the transformer was energized using the voltage close to the nominal grid voltage, the 2nd harmonic excited by the energization would become poorly damped and causes significant overvoltages which would likely damage the grid equipment. This is a classic example of harmonic resonance introduced in Chapter 3.

The previously mentioned observations raised the interest to study the measures to affect the segment resonance frequencies and consequently avoid the resonance and overvoltages. Figure 10 generalizes the observations from Publication I and illustrates the relations between: 1) the transmission network segment resonance frequency, 2) transmission network segment strength, 3) the capacitive reactive power of the transmission network segment Q_{CTL} and 4) the inductive reactive power of the shunt compensation Q_{LS}.

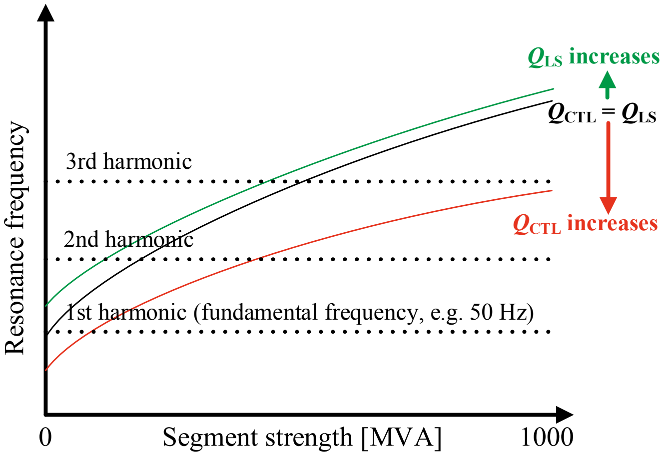


Figure 10. Development of the resonance frequencies. Modified from Fig. 4, Publication I. Q_{CTL} is the capacitive reactive power of the transmission network segment and Q_{LS} is the inductive reactive power of the shunt compensation connected to the segment. The black curve shows the situation where Q_{CTL} and Q_{LS} are equal. If Q_{LS} increases, the resonance frequency increases (green curve). If Q_{CTL} increases, the resonance frequency decreases (red curve).

Figure 10 shows that when Q_{CTL} and Q_{LS} are equal and the system strength is zero (i.e. the segment is disconnected and has no generation), the resonance frequency is equal to the 1st harmonic (i.e. fundamental frequency) of the system. Increasing the system strength (i.e. connecting more generation) increases the resonance frequency. Connecting capacitive elements (i.e. Q_{CTL} increases) decreases the resonance frequency (red curve). Respectively, connecting inductive elements (i.e. Q_{LS} increases) increases the resonance frequency (green curve).

The results lead to the conclusion that although the analyses would indicate no harmonic resonances in certain situations, the changes in the isolated system may shift the resonance frequencies and trigger the resonance as the restoration progresses. Such changes are likely during restoration when transmission lines and shunt compensation are connected. Thus, restoration planning should study the development of resonance frequencies during restoration and consider especially the variations in the system strength and connected inductive and capacitive elements.

Figure 10 also indicates that transmission line and shunt compensation reactance may a have significant impact on the resonance frequencies. Therefore, these parameters should be validated using measurements.

Publication I concludes that in the studied topology it was not possible to change either the system strength or the compensation level to avoid harmonic resonance and overvoltages. Thus, the transformer energization is not possible when the grid voltage is close to the nominal value at the time of the energization. Therefore, a new restoration procedure, *the gradual voltage build-up procedure* was developed. Publication I presents the procedure and Chapter 5 discusses this procedure as a measure to avoid uncertainties related to harmonic resonance during initial transmission network restoration. Respectively, Chapter 6 discusses the considerations for real-time system operations during restoration.

4.2.2 Synchronous Generator Self-Excitation

During the first field-tests of *the gradual voltage build-up procedure*, the protection relay tripped a reactor at Station 2 (Section 4.1, Figure 9) and caused the self-excitation of the black-start generator. Publication II analyzes the self-excitation and related issues in detail while Section 4.3.1 discusses the reactor trip.

Due to the reactor trip, the generator became connected to such a capacitive load that exceeded the generator reactive power capability. As discussed in Chapter 3, the generator lost the ability to regulate its terminal voltage and the self-excitation started. Figure 11 shows the uncontrolled voltage rise during self-excitation.

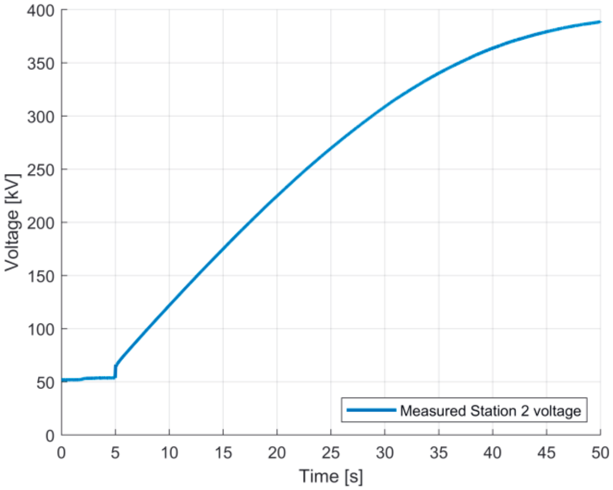


Figure 11. PMU measurements of the 400 kV transmission network voltage at Station 2 (Figure 9) during the generator self-excitation. When time is 5 s, a shunt reactor at Station 2 trips and the self-excitation starts.

Since the transmission network voltage was exceptionally low before the self-excitation, the self-excitation did not cause immediate overvoltages. Figure 11 shows that the measured Station 2 (Section 4.1, Figure 9) voltage rose close to the nominal 400 kV value in approximately 50 seconds after the reactor trip. The self-excitation ended when the generator was manually disconnected.

As shown by Publication II, if the reactor had tripped when the grid voltage was nominal, the self-excitation would have caused overvoltages which possibly damage the equipment and delay or even prevent the restoration using the specific restoration path.

The results presented in Publication II show that self-excitation simulations are sensitive to modeling inaccuracies. Therefore, there are significant uncertainties related to the modelling of the black-start generator excitation system in restoration studies. Thus, the modelling of black-start generator self-excitation requires special attention. Inaccuracies in the behavior of the generator field current and voltage, generator reactance or transmission network reactance significantly affect the simulation results. In addition, the excitation system UEL settings have a significant impact on the voltage rise during self-excitation. Publication II also shows that the detailed modelling of the interaction between the generator and the transmission network during self-excitation is not possible without reference measurement data from the specific generator and excitation system. Therefore, self-excitation simulations without simulation models validated against field-test data should be considered as highly inaccurate. Chapter 5 focuses on the management and the mitigation of self-excitation when planning restoration actions. Respectively, Chapter 6 focuses on the aspects related to real-time system operations during restoration.

4.2.3 Ferroresonance and Subsequent Sustained Parallel Resonance

Publication III presents *a ferroresonance and subsequent sustained parallel resonance* which occurred in 400 kV transmission network segment. The resonance may occur when the natural resonance frequency of a transmission network segment is close to the operating frequency of the source supplying the resonance circuit.

The resonance started when an already connected shunt compensated transmission network segment with a power transformer became disconnected. Figure 12 illustrates the network which is analyzed in Publication III. The resonance caused overvoltages possibly damaging the grid equipment with significant adverse consequences to the restoration

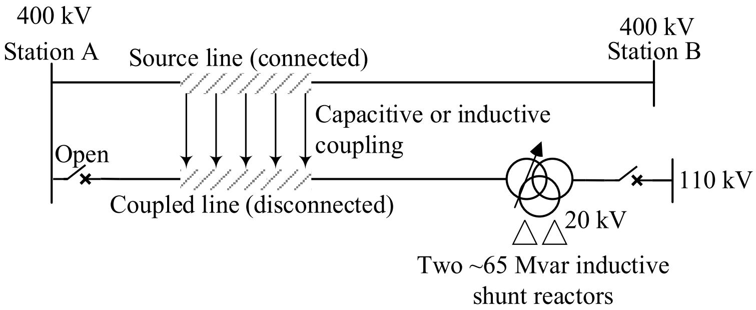


Figure 12. Schematic diagram of a grid where ferroresonance and subsequent sustained parallel resonance occurred. The 400 MVA transformer is equipped with an OLTC. The resonance occurred when the transmission network segment with a transformer became disconnected. A parallel connected transmission line at the same right-of-way supplied the sustained resonance circuit.

Such disconnection may occur, for example, when a segment is energized but becomes subsequently disconnected by, for example, unexpected protection actions. As Publication II shows, unexpected protection actions may occur during restoration and those may occur more likely during exceptional operating actions.

As analyzed in Publication III, the incident comprised two subsequent events: first a ferroresonance occurred, followed by a sustained parallel resonance. Together, these subsequent phenomena are here referred to *ferroresonance and sustained parallel resonance,* which exhibits the characteristics of both parallel line resonance and ferroresonance which were both introduced in Chapter 3.

Publication III shows that if the shunt capacitance of the coupled line (Figure 12) is almost completely compensated by a shunt reactor and the natural resonance frequency of the disconnected segment is below the operating frequency of the parallel source line (Figure 12), the disconnected segment is prone to a *ferroresonance and sustained parallel resonance*. If the resonance frequency of the disconnected segment is higher than the operating frequency of the parallel system, the resonance attenuates.

In certain power systems, the transmission line capacitances should be almost completely compensated to avoid voltage problems when restoring the networks into service or in light load conditions. As Publication III shows, such situation makes the networks with power transformers sensitive to a ferroresonance, which in turn may lead to a subsequent parallel resonance.

Publication III shows that special attention should be given to circumstances where the shunt compensation is connected to the network through a transformer having an OLTC. In such a topology, the tap position may have a significant impact on the natural resonance of the disconnected transmission network and the tap positions should be carefully analyzed when planning the restoration actions. As Publication III shows, in a such topology, the resonance may occur only at specific tap positions. Consequently, the resonance is sensitive not only to the electrical parameters of the transmission network but also how the transmission network is operated. This causes uncertainty for the identification of the situations making the transmission network prone to the resonance. Chapter 5 focuses on the management and mitigation of the *ferroresonance and subsequent sustained parallel resonance* when planning restoration while Chapter 6 presents aspects related to real-time system operations during restoration.

4.2.4 Parallel Line Resonance

Publication IV shows the significant delays that the parallel line resonance may cause during restoration. As introduced in Chapter 3, parallel connected transmission lines may cause high voltages to disconnected transmission network segments if the segment is almost 100 % shunt compensated.

In the field-tests, high induced voltages prevented connecting the black-start generator to the transmission network segment. As shown by Publications III and IV, the resonance frequencies of the test grid needed to be shifted to reduce the induced voltages.

After an actual system level blackout, during initial transmission network restoration, the parallel line resonance does not occur since the parallel network is not energized. However, the parallel line resonance may occur later during the restoration as parallel transmission lines have been restored. Chapter 5 and Chapter 6 summarize the considerations for restoration planning and real-time system operations during restoration.

4.3 Observations on Protection and Automation Systems

4.3.1 Shunt Reactor Protection

Publication II shows the critical role of inductive shunt compensation during restoration. The disconnection of a single shunt reactor may expose the transmission network to dangerous overvoltages due to black-start generator self-excitation.

In Publication II, a dry-type shunt reactor was disconnected by a compensated reactor unbalance protection relay. This type of dry-type shunt reactor has an ungrounded neutral and a double wye structure, illustrated in Figure 13.

The relay monitors the reactor unbalance current i_{Y12} (Figure 13) to detect internal reactor faults such as inter-turn short circuits or the break of a sub-conductor. In an ideal reactor, the current would be zero. In practice, however, the structure is not symmetric and there is a structural unbalance current i_{Y12}, unique to each reactor unit.

When the reactor is commissioned, the natural unbalance current is measured and compensated using a fixed setting in the relay parameters. During the commissioning, the reactor voltage is close to the nominal value. The value of the current compensation is fixed with the nominal voltage and the protection relay does not take into account the reactor voltage when measuring the current.

The relay measured the unbalance current i_{Y12} but also subtracted the fixed unbalance current compensation from i_{Y12} to take into account the structural unbalance current of the reactor. The fixed unbalance current compensation was tuned at the nominal grid voltage. However, due to the exceptionally low reactor voltage during *the gradual voltage build-up procedure*, the unbalance current i_{Y12} was small compared to the current at the nominal voltage. Since the setting for the unbalance current compensation was fixed, the difference between the fixed relay setting and the actual (small) unbalance current i_{Y12} caused the relay to trip the reactor.

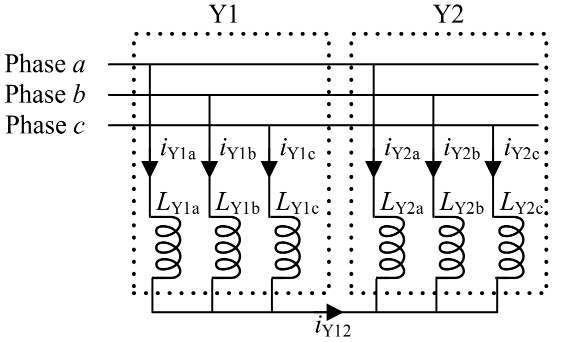


Figure 13. Schematic diagram of a double wye shunt reactor (dry-type) with an ungrounded neutral. Currents i_{Y1a}, i_{Y1b} and i_{Y1c} are the phase currents and L_{Y1a}, L_{Y1b} and L_{Y1c} are the reactor inductances of the first wye winding (Y1). Respectively, i_{Y2a}, i_{Y2b} and i_{Y2c} are the phase currents and L_{Y1a}, L_{Y1b} and L_{Y1c} are the reactor inductances of the second wye winding (Y2). Current i_{Y12} is the unbalance current between Y1 and Y2.

The shunt reactor protection performed according to the settings. This is an example of how unexpected protection actions may occur during restoration. Even if shunt equipment protection performs as expected during normal system operation, the exceptional voltages during restoration may trigger unexpected protection actions. Therefore, the shunt reactor protection issues or any relay setting issues may be difficult or impossible to identify without field-tests under actual restoration conditions. Chapter 5 discusses further the shunt reactor protection considerations for restoration planning. Respectively, Chapter 6 discusses the aspects related to the real-time system operations.

It is important to note that oil-immersed shunt reactors may have significantly different protection functions than dry-type shunt reactors discussed in this section. Thus, oil-immersed shunt reactors may have other protection functions which may cause issues during restoration. However, these are not in the scope of this thesis.

4.3.2 Automation and Protection of Black-Start Generator

Publication IV shows the variety of issues related to the black-start generator automation and protection encountered when performing restoration field-tests. As shown by Publication IV, such issues may significantly delay system restoration.

An interesting observation from Publication IV is that the generator black-start itself was always successful. Instead, either the connection of the generator or the energization of the transmission network segment using the generator failed.

The black-start generator automation issues were related to the start-up phase when the black-start generator was about to connect to the transmission network segment and start the segment energization. As reported by Publication IV, multiple attempts were made to connect the generator to the transmission network. However, the generator automation and excitation system protection disconnected the generator. This observation shows that testing only the black-start generator alone is not sufficient to detect possible issues related to the interaction between the generator and the transmission network. Therefore, in addition to the black-start generator itself, the field-tests should test the ability of the generator to energize the planned transmission network as well.

Identifying and solving the issues required special expertise in generator automation and protection systems. Such expertise is not likely available after a real blackout during system restoration. During the field-tests reported by Publication IV, issues of this kind delayed the execution of the tests for several hours even with the special expertise. In case of an actual blackout without all the expertise already in place, these issues might have had significant adverse consequences to the restoration. Chapter 5 discusses further how to manage and mitigate the issues related to the automation and protection of black-start generators when planning restoration. Respectively, Chapter 6 presents the considerations for system operations when executing restoration actions.

4.4 Methods to Identify Observed Uncertainties

4.4.1 Restoration Planning

The results show that simulations alone are not sufficient for the identification of the possible issues that may compromise fast and robust bottom-up restoration.

Therefore, the restoration planning should use both simulations and field-tests and apply an iterative planning process.

Simulation models are important for the planning of both restoration procedures and restoration field-tests as discussed further in Section 4.4.2 and Section 4.4.3. The results from the field-tests should be used to enhance both the restoration procedures and the simulation models.

Table 5 summarizes the considerations for the identification of the uncertainties related to restoration planning as discussed by Chapter 4.2 and Chapter 4.4.

Table 5. Considerations for the identification of the uncertainties related to restoration planning.

Harmonic resonance and transformer energization (Publication I) • Identification requires simulations with sufficient variations in the system strength and topology (capacitance and inductance). Snapshot simulations from a few cases are not necessarily sufficient. • Simulate the development of the system resonance frequencies as the restoration proceeds.
Synchronous generator self-excitation (Publication II) • Self-excitation simulations without field-test validated simulation models may be highly inaccurate. • Unexpected events during restoration are likely and may trigger the self-excitation in a weak system.
Ferroresonance and subsequent sustained parallel resonance (Publication III) • This may occur in a disconnected and close to 100 % shunt compensated transmission network with a transformer and an energy source (such as capacitively coupled transmission lines). Such disconnected transmission network may be formed, for example, by unsuccessful transmission network energization. • If shunt compensation is connected through a transformer with an OTLC, the tap changer position may have significant impact on the resonance occurrence.
Parallel line resonance (Publication III) • Like *ferroresonance and subsequent sustained parallel resonance*, this may occur in disconnected and close to 100 % shunt compensated transmission networks that have capacitively or inductively coupled connected transmission lines in parallel.
Shunt reactor protection (Publication II) • Unintentional relay protection actions may be impossible to detect in advance without field-tests. • Exceptional voltages and operational procedures during restoration may trigger unexpected protection actions although the protection systems perform as expected during normal system operation.
Automation and control systems of black-start generator (Publication IV) • It is practically impossible to identify automation and control system issues without field-tests. • Testing the black-start generator is not sufficient. The tests should also include the initial transmission network restoration.

4.4.2 Restoration Field-Tests

As the results show, the dynamics of the extremely weak system during restoration are completely different than the characteristics of the system during normal operation. Therefore, field-tests are required to identify the uncertainties related initial transmission network restoration.

The field-tests should cover at least the following elements:

1. the testing of the black-start generator itself,
2. the connection of the black-start generator to the transmission network suitable for connecting consumption and other generation to each other and
3. the restoration (energization) of the transmission network.

The field-tests should be planned using simulation models. Also, the possibility of unexpected incidents causing, for example, overvoltages should be considered. In addition, sufficient measurements are important when executing the field-tests. Section 4.4.3 discusses the simulation models and Section 4.4.4 the measurements.

4.4.3 Simulation Models

Simulation models are required for planning the restoration procedures and field-tests. In addition, simulation models are required for validating restoration actions that cannot be tested in practice using field-tests. Therefore, simulation models have a critical role in the identification of relevant weak network dynamics and factors that may affect the bottom-up restoration. Consequently, inaccurate simulation models may pose significant uncertainty for the restoration planning process.

Table 6 presents considerations related to the modeling of electrical phenomena and black-start generator automation and protection systems in restoration studies. Since the dominant system dynamics during restoration are completely different than during normal operation, simulation models tuned for the normal system operation may not be suitable for restoration studies. Therefore, the models should be prepared specifically for system restoration and then the models should be tuned using reference data from either real restoration actions or restoration field-tests.

Table 6. Considerations related to the modeling of electrical phenomena and black-start generator automation and protection systems in restoration studies.

Harmonic resonance and transformer energization (Publication I) • System resonance frequencies are highly influenced by the system capacitance and inductance. These parameters may be validated using measurements during normal system operation. • It is practically impossible to perform field-tests to validate the overvoltages caused by harmonic resonance in a weak system since the overvoltages may damage the grid equipment. • Transformer energization transient under no-resonance conditions may be validated using field-tests during normal system operation. • Special attention should be given to the modeling of the transformer saturation characteristics. Also, it is important that such data is available, for example, from transformer factory acceptance tests.
Synchronous generator self-excitation (Publication II) • Modelling the detailed response of the generator and especially the excitation system during self-excitation is not possible without reference measurements. • Special attention should be given to the possible chains of events or sequences that may cause black-start generator self-excitation.
Ferroresonance and subsequent sustained parallel resonance (Publication III) • The detailed EMT modelling of transmission line coupling (capacitive and/or inductive) and transformer saturation characteristics is required. • With shunt compensation connected to transformer tertiary winding, special attention should be given to the OLTC tap positions during simulations.
Parallel line resonance (Publication III) • Like *ferroresonance and subsequent sustained parallel resonance*.
Shunt reactor protection (Publication II) • The modelling of protection issues requires the detailed modelling of protection systems. • In case of compensated unbalance protection, the natural unbalance current is unique to each shunt reactor. Therefore, such protection settings should be modelled independently for each shunt reactor.
Automation and control systems of black-start generator (Publication II, IV) • The modelling of generator automation system sequencies and related protection systems would be practically impossible without assistance from the equipment manufacturers.

4.4.4 Measurements

The measurements should enable capturing system dynamics and enable validating and enhancing both restoration procedures and simulation models. In addition, the measurements should make it possible for control center operators to identify the encountered issues and perform corrective actions.

Although SCADA measurements and event lists are important, Publications I–IV show that the identification and analysis of the issues encountered during the practical testing were not possible using only SCADA measurements for the following reasons:

1. time resolution of the measurements was not feasible to capture the transient phenomena,
2. measurements were not time-synchronized making it impossible to determine the sequences of events and
3. the accuracy of the measurement was not consistent as shown by Publication IV.

PMUs are satellite time-synchronized and have better resolution than SCADA measurements. TFRs enable analyzing detailed voltage and current waveforms. Therefore, PMU and TFR measurements should be available to the control center from the substations and generators participating in the early stages of the restoration as follows:

1. PMU recorded voltage and current phasors and frequencies from the black-start generator and the initial transmission network should be used to monitor the restoration in real-time and to identify and analyze unexpected incidents such as generator self-excitation.
2. TFR recorded voltage and current waveforms should be available for the analyses of unexpected events such as *ferroresonance and subsequent sustained parallel resonance*.
3. Black-start generator field voltage and current from the excitation system should be used to monitor *the gradual voltage build-up procedure* in real-time.

In certain black-start generators, the generator SCADA system may record the excitation system performance. However, as Publication II shows, the excitation system performance should be measured using a dedicated TFR especially during field-tests. Typical excitation system quantities to be measured are the field voltage and current. However, the availability of these quantities depends on the type of the generator excitation system.

5 PLANNING OF TRANSMISSION NETWORK RESTORATION

This chapter continues the analyses in Chapter 4 but focuses on the restoration planning perspective. First, the chapter summarizes the lessons learned from Chapter 4 and concludes how the restoration planning process should be enhanced to be able to identify and manage the uncertainties reported by Chapter 4. After that, the chapter proposes an enhanced process for the planning of the initial transmission network restoration. Next, the chapter provides measures for restoration planning to manage and mitigate the uncertainties related to the electrical phenomena reported by Chapter 4. Finally, the chapter presents considerations on protection and automation systems from the restoration planning perspective.

5.1 Lessons Learned for Restoration Planning

As concluded in Chapter 4, simulation models alone are not sufficient for restoration planning. Restoration field-tests are required to identify possible issues which may compromise fast and robust system restoration. Publication IV summarizes the significant impact of both restoration field-testing and training on the restoration execution. The first tests, where the unexpected incidents reported by Chapter 4 were encountered, took about 12 hours. However, once the problems were solved and the restoration procedures revised, the black-start and initial transmission network restoration together took 27 minutes under the test conditions.

It is obvious that the entire power system restoration plan cannot be tested in practice in the field. As shown in Chapter 4, however, testing only the black-start functions of the generator is not sufficient either to ensure fast and robust restoration. Therefore, the feasibility for restoration field-tests should always be evaluated and field-tests should be an integral part of the restoration planning.

Chapter 4 shows that due to the dynamics of a weak network, the system behavior during the early stages of the restoration is practically impossible to study using only simulations. Therefore, in addition to the black-start generator tests, at least the initial transmission network restoration must be tested in practice.

Furthermore, the proper planning of field-tests is important. As discussed in Chapter 4, the critical substations and generators participating the early stages of the system restoration should be equipped with sufficient measurements.

As discussed in Publication IV, restoration field-tests are valuable also for the training of procedures and control center tools for operational personnel. In addition, restoration field-tests provide an opportunity for the operational personnel to suggest improvements to the procedures and control center tools. Those suggestions may make the restoration plan and the relevant documentation easier for operational personnel to follow during real emergencies.

Performing the field-tests may reduce the operational security of the transmission network during a short time and trigger overvoltages that may possibly damage grid equipment. However, Chapter 4 shows that if restoration procedures are not tested in the field and procedures rely completely simulation and on black-start generator tests, the restoration process may encounter electrical phenomena and automation and protection system issues which may delay or even prevent the restoration. Therefore, both the risks of field-testing and the risks of not performing the tests should be evaluated and understood.

5.2 Proposed Planning Process

5.2.1 Overview

Figure 14 presents the proposed process when planning the initial transmission network restoration for bottom-up restoration. This process aims at:

1. identifying the possible uncertainties related to the initial transmission network restoration using both field-tests and simulations,
2. validating the restoration procedures and simulation models
3. training the restoration procedures for operational personnel and improving the control center tools and operational procedures to support restoration.

The phases of the process are described in Section 5.2.2. The process highlights two key observations from Chapter 4. Firstly, the field-tests should be mandatory and should also include initial transmission network restoration. The initial transmission network should allow the connection of consumption and other generators to the black-start generator. If the initial restoration plan cannot be tested at all, the plan should be revised to enable testing. Secondly, the results from the field-tests should be used to validate and revise (if necessary) the restoration procedures and simulation models.

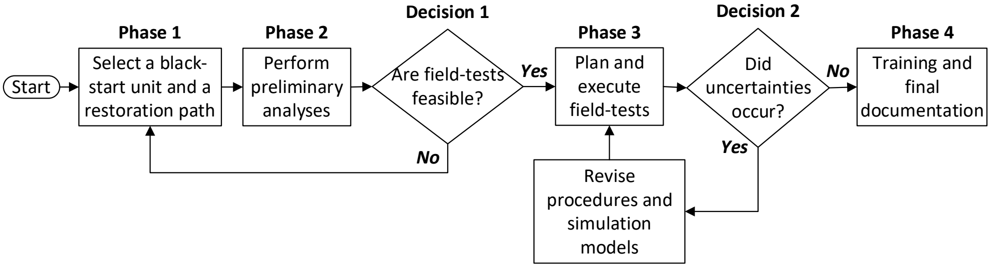


Figure 14. The proposed process for the planning of the initial transmission network restoration. The process has four phases (Phases 1–4) and two decisions (Decision 1 and Decision 2).

It is important to note that the process presented in Figure 14 does not apply for the planning of the entire power system restoration. Instead, the process applies for the planning of the initial transmission network restoration which covers the critical early stages of the bottom-up restoration. Therefore, the proposed process presented in Figure 14 complements the existing processes and methodologies for entire system restoration planning which were discussed in Chapter 2.

5.2.2 Phases of the Proposed Planning Process

The process (Section 5.2.1, Figure 14) has four phases and two decisions that must be made.

Phase 1. In this phase, the black-start generator and the transmission network for the initial restoration are selected. The transmission network with the black-start generator must enable connecting the consumption and other generation in the later phases of the restoration.

Phase 2. Preliminary analyses are performed to identify possible uncertainties related to the black-start and initial restoration of the segment. The analyses should also study the feasibility of the field-tests, i.e. that the restoration field-tests may be performed in practice.

Decision 1. If the field-tests seem feasible, the planning continues to the next phase. However, if the field-tests are not feasible, the process goes back to Phase 1 to select a topology making it possible to perform the field-tests.

Phase 3. Restoration field-tests must be properly planned and executed with measurements during the tests. The measurements must be carefully analyzed after the tests.

Decision 2. If uncertainties requiring further actions are not identified, the process continues to the next phase. However, if uncertainties were encountered, the processes or models must be revised, and the tests should be performed again.

Phase 4. The training and documentation of the procedures are important. Field-tests should also be a part of the training. It is important that the restoration procedures can be trained using a SCADA integrated training simulator.

5.3 Mitigation of Unwanted Electrical Phenomena

5.3.1 Harmonic Resonance during Transformer Energization

Chapter 4 shows that harmonic resonance may prevent conventional transformer energization when the grid voltage is close to nominal value at the moment of energization. Publication I presents *the gradual voltage build-up procedure*, which enables the gradual energization of a selected transmission network and transformers even when the harmonic resonance would prevent the conventional network restoration. The simulations and field-test results in Publication I shows that the soft energization of transmission lines and transformers enable transmission network restoration despite the harmonic resonance. Since transformer voltages increase gradually, the transformer inrush current and its harmonic content are negligible and do not excite the resonance and consequent overvoltages.

The reactive power capability of the black-start generator used for the gradual voltage build-up procedure should be verified with field-tests. The generator must be able to supply reactive power required by the network being energized.

The black-start generator must be also able to operate at very low active power output during *the gradual voltage build-up procedure*. Since there is no consumption connected to the network, the black-start generator supplies only the losses of the network connected to the generator.

Special attention should be given to the protection of the black-start generator and transmission network during the procedure. When the system voltage is exceptionally low, normal protection arrangements may not be fully functional.

As discussed in Chapter 4, the development of harmonic resonance frequencies during restoration should be carefully studied. Especially, restoration planning should study, in advance, measures to increase the system strength above the harmonics triggered by transformer energization. Consequently, the segments used for the initial transmission network restoration should enable the connection of other generators to the system to increase the system strength.

Conventional transformer energization (i.e. using nominal grid voltages) should be avoided until the system resonance frequencies are higher than the harmonics triggered by the transformer energization. Until then, the transformers should be energized with gradually increasing voltages using the generators that are being started up and are about to connected to the system. This way, the transformer switching transients may be avoided until the system is strong enough.

In addition, the restoration planning should aim at specifying the operating conditions when harmonic resonance may be an issue. These limits should clearly be stated in the restoration instructions for the operators.

5.3.2 Synchronous Generator Self-Excitation

Chapter 4 and Publication II show that unforeseen events during restoration may trigger generator self-excitation. Therefore, the possibility of black-start generator self-excitation should be considered in the restoration planning and the remedial actions should be prepared in advance although self-excitation would seem unlikely.

As shown by Publication II, the generator excitation system and especially UEL have a significant impact on the voltage rise during self-excitation. Especially, the UEL setting value is more significant than the response time of the UEL. The UEL settings should maximize the reactive power absorption capability of the generator, however, without risking the stability of the generator. Therefore, the UEL settings and the reactive power capability of these generators participating the early stages of the restoration should be verified and tested when planning restoration. Also, the UEL settings and reactive power capabilities of the generators should be regularly verified and tested when the generators have a critical role in a restoration plan.

Publication II shows that negative field current capability of the generator only temporarily limits the voltage rise during self-excitation. However, this applies only to the situation where a single generator is connected to the system.

As discussed in Publication II, protective measures against self-excitation and overvoltages may also be applied. Overvoltage relays should automatically connect additional shunt compensation to the system and reduce the capacitive load of the generator and voltage rise. However, special attention should be given to the performance of the protection functions in case of exceptional grid voltages.

5.3.3 Ferroresonance and Subsequent Sustained Parallel Resonance

Chapter 4 and Publication III analyze the issues and mitigation of *the ferroresonance and subsequent sustained parallel resonance*. Topologies prone to the resonance may be difficult to avoid during restoration.

As shown in Publication III, *the ferroresonance and subsequent sustained parallel resonance* attenuates, if the resonance frequency of the segment is higher than the frequency of the supplying source. Therefore, transmission network segments should be inductively overcompensated (i.e. have extra inductive shunt compensation). In other words, the inductive reactive power of the connected shunt compensation should be greater than the capacitive reactive power of the transmission lines and other equipment connected to the segment. Extra inductive shunt compensation rises the resonance frequency of the segment over the operating frequency of the supplying source. However, the possible issues such as voltage problems due to overcompensation should be considered.

Publication III also highlights the importance of considering the impact of OLTC tap position on the natural resonance frequencies in topologies where shunt compensation is connected through a power transformer with an OLTC. In such topologies, the OLTC tap position may be used to shift the resonance frequency away from the problematic area. On the other hand, an unfavorable tap position may accidentally trigger the resonance. Thus, restoration planning should calculate the allowed tap position variations in advance the allowed positions should be properly documented in the restoration instructions.

5.3.4 Parallel Line Resonance

The measures to mitigating *ferroresonance and subsequent sustained parallel line resonance* are also sufficient for mitigating parallel line resonance.

5.4 Considerations on Protection and Automation Systems

5.4.1 Shunt Reactor Protection

As Chapter 4 shows there may be significant uncertainties related to the shunt reactor protection performance in certain protection configurations during restoration. As Chapter 4 discusses, this may especially be an issue with specific protection relays, such as unbalance protection, that uses fixed compensation settings. It is important to note that oil-immersed shunt reactors may have very different protection functions than dry type shunt reactors discussed in Chapter 4.

Since transmission network voltages may be exceptional during restoration, the shunt reactor protection settings should consider the actual value of the system voltage and adapt their performance as the voltage changes. As Chapter 4 shows, this is especially the case with relays that use measurement-based compensation, such as compensated unbalance protection relays.

Restoration field-tests are important in ensuring robust shunt protection performance during restoration. In addition, the measurement data from the restoration field-tests may be used to test those compensation devices that may not be field-tested. The protection parameters should be such that the compensation stays connected even in case of exceptionally low voltages.

In addition, it should be considered whether the tripping of certain sensitive protection functions could be replaced with an alarm during restoration. This might be justified especially with dry-type shunt reactors in situations where the unintentional trip of a single shunt reactor would cause overvoltages and potentially damage multiple grid equipment. After receiving the alarm, the operators could prepare the transmission network for the reactor disconnection and manually disconnect the reactor. However, the risks of disabling the tripping by certain protection functions should be carefully evaluated. In case of oil-immersed reactors, such arrangements may not be feasible due to fire and environmental issues.

As an example, the following modifications to the dry-type shunt reactor protection were made after the self-excitation incident reported in Publication II to ensure that the shunt reactors stay connected during restoration. Firstly, the parameters of the compensated unbalance protection were revised to allow larger unbalance currents. Secondly, the most sensitive unbalance protection functions provide only alarm.

5.4.2 Automation and Protection of Black-Start Generator

Chapter 4 shows that systematic field-testing is critical to mitigate the uncertainties related to black-start generator automation and control systems. In addition, Publication IV shows that automation sequences for black-start generator start-up and transmission network restoration enhance the execution of restoration actions. However, the testing of the automation sequences in advance is important.

5.4.3 Substation Auxiliary Backup Power

Substation backup power must be able to provide the power required by the substation control actions during restoration. Power transformer OLTCs are driven by large motors and may require special attention since a backup battery may not necessarily provide sufficient power for the OLTC operations.

In the restoration procedures presented in this thesis, OLTC operations are in a significant role. *The gradual voltage build-up procedure* requires that transformer OLTC tap positions are controlled to specific positions before the transmission network is restored. In addition, OLTC operations may be needed to tune transmission network resonance frequencies to avoid *ferroresonance and subsequent parallel resonance*. These aspects impose two requirements for the substation backup power:

1. the substation must be able to provide control center SCADA reliable status information about the current tap position during a blackout and
2. it must be possible control the tap position of large power transformers remotely during a blackout.

6 MANAGING UNCERTAINTIES DURING REAL-TIME OPERATION

This chapter continues the analyses in Chapter 4 and Chapter 5 but focuses on the real-time system operations perspective. This chapter proposes how the uncertainties presented in Chapter 4 and the measures presented in Chapter 5 should be considered in system operations when restoring the system from a blackout. First, the chapter discusses the importance of preparedness in advance for exceptional events. After that, the chapter highlights the importance of properly designed controls center tools and the role of restoration training. Finally, the chapter presents measures to manage unwanted electrical phenomena and considerations on protection and automation systems when executing restoration actions.

6.1 Implementation of Restoration Procedures

6.1.1 Importance of Preparedness

The uncertainties discussed in Chapter 4 are seldom encountered during normal system operation. The existence of such uncertainties impacting the restoration might not even be recognized without practical experience from the issues. However, as Chapter 4 shows, restoration procedures may trigger the unexpected chains of events even in a small system including only a single generator and few transformers and transmission lines.

As discussed in Chapter 5, the mitigation of the uncertainties requires procedures that are very different from normal system operation. In addition, special expertise from many areas may be required to solve the possible issues when those are encountered for the first time. Based on the results presented in Chapter 4 and Chapter 5, it is evident that solving the issues during an emergency without proper preparations is challenging, or even impossible, and may significantly delay the restoration. Therefore, the procedures must be prepared, instructed and trained in advance. As Publication IV shows, systematic field-testing and training of the restoration procedures significantly reduces the impacts of the uncertainties.

6.1.2 Use of Remote Control and Automation

As Chapters 4 and 5 discuss, the initial transmission network restoration requires specific procedures performed at both the black-start generator and the transmission network. A failure to follow the procedures, for example, due to a human error may likely lead to the abort and restart of restoration. This may significantly delay the process and consume the invaluable time during the restoration. In the worst case, a human error may cause equipment damage and consequently prevent restoration using the specific route.

Publication IV shows that remotely controlled black-start and predefined generator automation sequencies for transmission network restoration enabled the black-start and the initial restoration in less than 30 minutes under test conditions. Remote control reduces the need for local operations on the power plant and preconfigured automation sequences reduce the risks of human errors. As described by Publication IV, however, the implementation restoration process required iterative field-tests and training in the transmission network.

The generator black-start and transmission network restoration procedures can be divided into suitable steps and programmed into automation systems. Using remote control, the operator may perform the black-start and initial transmission network restoration step by step. The programmed sequences may guide the operator to perform the restoration according to the predefined process.

6.1.3 Control Center Displays and Measurements

As discussed in Chapter 4, the SCADA measurements are not sufficient for the identification and analyses of the possible issues during restoration. In addition to SCADA measurements, more detailed measurements such as PMUs and TFRs are also needed. The measurements, easy access to the data and the control center displays should be planned and implemented in advance so that the displays and data are quickly available for system restoration. In addition, the sufficient training of operational personnel to interpret the measurements is important.

Chapter 5 shows that the mitigation of unwanted electrical phenomena during restoration requires specific control actions in the transmission network. Therefore, control center SCADA displays should be intuitive and support the execution of the restoration procedures according to the instructions:

1. the displays should easily visualize the transmission network status during black-start and initial restoration,
2. shunt compensation statuses and transformers OLTC positions should be easily identified and controlled,
3. black-start generator controls should be easily available.

The displays should be designed together with the control center operators to get their feedback. Restoration field-tests are useful also for testing the displays.

6.1.4 Training

Chapters 4 and 5 show that the regular training of the control center operators is important. At least, the following aspects should be considered in the training.

1. Control center operators or dispatchers should be aware of the possibly encountered electrical phenomena and protection and automation system issues during restoration to be able to understand the system behavior and measurements. However, detailed theoretical understanding is not required.
2. Operators should understand what control actions may trigger the unwanted electrical phenomena.
3. Operators should understand what control actions may be used to manage and mitigate the unwanted electrical phenomena.

The training requirements for the electrical phenomena are discussed in Section 6.2.

SCADA integrated training simulators such as a DTS or OTS (introduced in Chapter 2) are useful for restoration training. Although the simulators may not simulate the exact electrical response of the system, the possible issues and electrical phenomena may be simplified so that the system provides a realistic look and feel. Field-test data are important for such simplification.

6.2 Managing Unwanted Electrical Phenomena

6.2.1 Harmonic Resonance and Transformer Energization

Chapter 5 presented *the gradual voltage build-up procedure* as a measure to gradually restore both transmission lines and large power transformers and manage the issues related to harmonic resonance. Since the procedure is highly different to the normal system operation, special attention should be given to the training and SCADA displays to support the procedure execution.

As discussed in Chapter 4, the resonance characteristics of the system change as the restoration proceeds. Therefore, the restoration instructions should specify when the system strength has increased so that the harmonic resonance becomes unlikely. The SCADA system real-time calculations may assist in monitoring the connected generation. It may also be possible to implement close to real-time short circuit current calculations. Consequently, the SCADA could provide an alarm when the specific limits of system strength are exceeded.

As discussed in Chapter 5, although the initial transmission network restoration was performed using *the gradual voltage build-up procedure*, the energization of the following transformers may excite the harmonic resonance. Therefore, generators being connected to the system should use soft energization to energize their transformers before synchronizing to the system. This is critical until the system strength has increased sufficiently and harmonic resonance is not a concern.

6.2.2 Synchronous Generator Self-Excitation

Chapter 4 discussed the issues related generator self-excitation. Since the uncontrolled voltage rise due to synchronous generator self-excitation may occur fast, the control center operations may not have much time to manually react to self-excitation. Thus, the measures to mitigate self-excitation should be prepared when planning restoration as discussed in Chapter 5.

Control center operators should understand the possibility of self-excitations when executing switching actions in a weak system. As introduced in Chapter 3, self-excitation occurs when a generator becomes connected to such a capacitive load that exceeds the reactive power capabilities of the generator.

In Publication II, the self-excitation was caused by an unintentional shunt reactor trip. However, other switching actions during restoration may also trigger self-excitation. For example, the connection additional transmission lines without sufficient inductive shunt compensation during restoration may cause a similar capacitive load. Similarly, the disconnection of another generator in the system may increase the capacitive load of the remaining generators and trigger the self-excitation. This is important to consider in the restoration instructions and training so that the operational personnel may avoid self-excitation during restoration.

The restoration instructions and training should also include the operational procedures to end self-excitation if it occurs. Connecting enough additional inductive shunt compensation is an obvious measure to end self-excitation. Similarly, if self-excitation occurs and there is only one generator connected, the generator disconnection is also an obvious measure to end the self-excitation. However, if multiple generators are connected, the generator disconnection increases the capacitive load of the remaining generators and therefore makes the situation worse. Therefore, the restoration instructions and training material should take into account the number of connected generators.

6.2.3 Ferroresonance and Subsequent Sustained Parallel Resonance

Chapter 4 discussed the issues related to *the ferroresonance and subsequent sustained parallel resonance* which may occur when an almost completely shunt compensated transmission network segment with a power transformer becomes disconnected. As discussed in Chapter 5, connecting extra inductive shunt compensation to the segments attenuates the resonance. This is important to consider when restoring the transmission network segments into service.

As discussed in Chapter 5, if shunt compensation is connected to the segment through a transformer equipped with an OLTC the tap positions may have significant impact on the segment resonance frequencies. Therefore, restoration planning should calculate the safe ranges of tap positions in advance and those ranges should be strictly followed in the system operations when restoring the segments into service. Special attention should be given to control center SCADA displays. The displays should visualize the current tap positions and target tap positions before the segment is restored into service.

Publication III shows that already triggered *ferroresonance and subsequent sustained parallel resonance* may be attenuated by increasing the resonance frequency of the transmission network segment higher than the operating frequency of the supplying source. However, the tuning of the segment resonance frequencies may be a challenging task during an emergency. Therefore, special attention should be given to the training and instructions of such procedures.

6.2.4 Parallel Line Resonance

As discussed in Chapter 4, parallel line resonance may occur as the restoration progresses. Therefore, it is important that the control center operators understand the possibility for the parallel resonance during restoration. As discussed in Chapter 5, the measures to mitigating *ferroresonance and subsequent sustained parallel line resonance* are sufficient for mitigating parallel line resonance as well.

6.3 Considerations on Protection and Automation Systems

6.3.1 Shunt Reactor Protection

Chapter 4 presented issues related to shunt compensation protection settings during system restoration. It is important that the control center operators understand the critical role of the inductive shunt compensation during restoration. Insufficient inductive shunt compensation may make the system prone to synchronous generator self-excitation and *ferroresonance and subsequent sustained parallel resonance*.

As discussed in Chapter 5, in certain situations some protection functions could provide an alarm instead of tripping the reactor during restoration. In other words, some protection functions would provide an alarm before the shunt reactor will be tripped. Therefore, the control center operators would have time to adapt the system for the reactor disconnection and manually disconnect the reactor. However, special attention should be given to the training of the control center operators if such protection configurations are applied.

6.3.2 Black-Start Generator Automation and Protection

As discussed in Chapter 5, it is critical that black-start generator automation and protection are planned and tested in advance during restoration planning. In addition, automation sequences may significantly enhance the execution of restoration actions. However, it is important that control center operators are regularly trained for using the functionalities.

7 DISCUSSION AND FUTURE WORK

This chapter discusses the results and presents recommendations for future work. The discussion is divided into four sections. First, the chapter focuses on aspects related to the robust restoration of critical systems. After that, the chapter discusses the needs for broader dissemination of the lessons learned during restoration. Next, the chapter discusses the needs for new requirements for the practical testing of restoration plans. Finally, the chapter assesses the validity of the results of the thesis.

7.1 Enabling Robust Restoration of Critical Systems

In addition to power system restoration, the results of this thesis may be applied in other critical procedures. Generally, the thesis shows that special attention should be given to procedures which are seldom executed in practice, difficult to test and are highly different than normal system operation. Power system restoration is an example of such a procedure. Where the normal power systems operation is performed with established processes, the processes related to the system restoration are highly different and seldom executed in practice. Consequently, the utilities do not have much practical experience about the restoration. Therefore, preparedness for restoration actions and sufficient training and practical testing are important.

Without reference measurements from the field, the processes must be modelled based on sophisticated assumptions. This thesis shows that in case of power system restoration, it is practically impossible to identify the uncertainties related to the process without reference measurements from the field. As shown by the thesis, unresolved issues may have significant adverse consequences to the restoration. Therefore, the field-testing of critical processes is necessary. In other words, theoretical modelling and sophisticated assumptions alone are not enough.

Preparing for system restoration is an essential part of real-time power system management. Publication V shows that even during normal power system operation, the system characteristics vary, and the variations may be difficult to predict. The observation highlights the complex nature of power systems and the challenge of making assumptions related to the power system operation. Therefore, the utilities responsible for power systems, and other similar critical systems and processes, should systematically monitor and analyze the system behavior both during normal operation and in case of exceptional events. The utilities should use this information to prepare and update operational instructions and have regular training for the management of unexpected events.

7.2 Dissemination of Lessons Learned

Future work is required concerning international forums disseminating the lessons learned during restoration. The importance of sharing the lessons learned during restoration has been recognized already in the 1980s by the IEEE task forces [1, 20]. In 2004, NERC [10] and North American 2003 blackout task force concluded [11] again the need for the dissemination of lessons learned during restoration. However, in 2015 CIGRE concluded [3] that there are not any descriptions of restoration processes publicly available. This thesis repeats this observation.

Typically, the public disturbance reports of blackouts pinpoint the root causes of disturbance and present the flow of restoration actions only at a general level. However, the systematic analyses of the encountered issues and best practices during restoration have received less attention in the literature and public forums.

It is understandable that detailed restoration procedures are not publicly available due to their sensitive nature. Also, it is acknowledged that each power system has specific considerations related to system restoration processes. Therefore, there is not a single restoration process that could be implemented as such for every system.

It is essential for the industry to share lessons learned from different types of power systems: what kind of procedures, processes or practices help the system restoration and what kind of procedures should be avoided. In addition, to the restoration procedures itself, this discussion may help developing the control center tools and visualization of complex and possibly unintuitive restoration processes. In addition, the power systems are changing due to the integration of renewable energy sources. New types of generation may have significant impact on the existing restoration procedures. Therefore, future work and disseminations should also cover the aspects related to new types of generation and system restoration.

7.3 Considerations on Requirements for Restoration Tests

Future work is required concerning the requirements for practical testing of restoration plans. As this thesis shows, the black-start and the initial transmission network restoration, which establishes the starting point for the remaining system restoration, should always be tested in practice. It is obvious that the entire restoration plan cannot be validated using field-tests. However, at least the black-start and the initial transmission network restoration should be tested.

For example, the European legislation [29] requires the black-start generator testing but the testing of the transmission network restoration is not mandatory. Respectively, NERC requires [30] a black-start tests and the energization of a bus but does specify further testing requirements for transmission network restoration. However, this thesis shows that the black-start generator tests are not sufficient, and the initial transmission network restoration should always be tested in practice. Therefore, it should be evaluated whether such tests should be considered mandatory in regulation and requirements and how such requirements could be implemented in practice. In any case, restoration field-testing is highly recommended in the light of the results presented in this thesis. Also, restoration field-tests with sufficient measurements were necessary to obtain reference data for the calibration of simulation models for restoration studies.

Even accurate simulation models may not be sufficient for the validation of the procedures. As this thesis shows, applied control settings such as power transformer OLTC tap positions may have a significant impact on the simulation results. Therefore, field-tests are required to validate the procedures with the parameters that are applied in the real system. Furthermore, the revalidation of the procedures should be considered if the parameters are changed.

In high voltage transmission networks, even the regional field-testing of the restoration procedures may reduce the security of the system for short duration and require complex arrangements. In addition, possible electrical phenomena, as reported in this thesis, may damage the grid equipment. Therefore, it is important to evaluate the risks of both performing the restoration field-tests but also the risks of not field-testing the restoration procedures. As this thesis shows, the consequences of not field-testing the restoration procedures may be significant and may not realize until in a real emergency when restoring the system from a blackout.

Although the uncertainties presented in the thesis may appear unrealistic during normal operation, they may be encountered during the unconventional procedures required for system restoration. As the modern power systems become more complex and interconnected, the preparedness for exceptional incidents becomes even more important. Field-testing the restoration plans enhances the preparedness for exceptional and unforeseen incidents and ensures the robust restoration procedures also for the power systems of the future.

7.4 Assessment of the Validity of the Results

Each power system has system specific characteristics that must be considered when planning restoration. Therefore, the analyses and results presented in this thesis also reflect the characteristics of the Finnish power system. However, the uncertainties presented by this thesis may be encountered in other power systems as well.

The ferroresonance and subsequent parallel resonance presented in this thesis occurred in a topology, where shunt compensation is connected to the transmission network through a power transformer with an OLTC. It is important to note that such resonance may also occur in different topologies. However, the principles presented by this thesis to manage the resonance may be applied in different topologies although the detailed control actions on the transmission network might be different.

System protection configurations are highly power system specific. This thesis focused on a specific issue with dry-type shunt reactor protection. However, it is likely that other types of protection issues may also be encountered. In addition to dry-type shunt reactors, the protection of oil-immersed reactors should also be studied. Furthermore, the automation and protection of black-start generators may also have generator specific aspects. Therefore, power system and generator specific assessment is required to understand the uncertainties related to the automation and protection systems in each power during restoration.

Assessing the performance of the transmission system protection is especially important when applying the *gradual voltage build-up procedure* since the exceptionally low voltage may significantly affect the protection. Therefore, future work should focus on the uncertainties related to the protection performance in case of exceptionally low voltages during restoration.

In certain power systems, there may be multiple transmission system operators or independent system operators responsible for the system restoration. In certain situation, the distribution system operators may also have a significant role. The results of this thesis may also be applied in such systems, but special attention should be given to the co-operation between the utilities responsible for the restoration.

During restoration, power system frequency may vary significantly as the consumption and generation is restored. Since transmission network reactance is frequency dependent, the frequency variations may significantly influence both the resonance frequencies and the reactive power balance during restoration. However, analyzing frequency variations is out of the scope of this thesis. Therefore, future work should also study the impacts of frequency variations on resonance frequencies, reactive power balance and system voltages.

8 CONCLUSIONS

The thesis describes the framework of initial transmission network restoration and presents three main contributions. First, this thesis proposes methods for identifying uncertainties related to restoration planning and execution and assessing the impact of the uncertainties. Secondly, this thesis presents means and measures to enhance restoration planning to identify and manage the uncertainties and mitigate their impact. Thirdly, this thesis presents means and measures to manage the uncertainties of electrical phenomena and protection and automation systems during restoration.

System restoration is very different from normal system operation. The thesis presents an iterative process for restoration planning. Uncertainties related to the electrical phenomena and protection and automation systems cannot be identified using only simulations. Therefore, restoration field-tests with accurate measurements are required to identify uncertainties. It is evident that entire power system restoration plans cannot be field-tested. However, the black-start and the initial transmission network restoration, which establishes the starting point for the rest of the system restoration, should always be tested in practice.

Dominant system dynamics are highly different during restoration than during normal operation. Therefore, simulation models used for normal system operation are not sufficient for restoration planning. Thus, restoration field-tests are required to obtain reference data for calibrating the simulation models for restoration studies. In addition to conventional SCADA measurements, PMU and TFR measurements are required to identify the uncertainties and obtain the reference data.

The thesis analyzed four electrical phenomena and presented measures to mitigate the possible adverse impacts of the phenomena when planning and executing system restoration: 1) synchronous generator self-excitation, 2) harmonic resonance and switching transients, 3) ferroresonance and subsequent sustained parallel resonance and 4) parallel line resonance. The mitigation measures should be prepared in advance and trained for the operational personnel regularly.

Black-start remote control and automation may significantly enhance the restoration and reduce the risks of human errors when performing restoration procedures that are highly different than normal system operation. However, the testing, validation and regular training of the procedures is important.

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PUBLICATIONS

PUBLICATION
I

Fast restoration of a critical remote load area using a gradual voltage build-up procedure

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Abstract: This study validates an alternative restoration of a critical load area using remote black-start units. Using the conventional restoration, switching actions on a nominal system voltage create switching transients, especially when energising a transformer. The transients maybe close to the resonance frequencies of a weak island system, which may induce high voltages, delay the restoration and damage the equipment in the grid. This study proposes an alternative restoration procedure where, to avoid switching transients, hundreds of kilometres of transmission lines and several transformers are energised using a gradually increasing voltage, which is controlled by the synchronous generator exciter. This study presents detailed procedure flowcharts, a proof of concept for the proposed procedure using a Finnish and an Austrian field tests and theoretical analyses of the tests. The results show that with the gradually increased voltage, harmonic resonances and switching transients during the initial system energisation maybe avoided. In addition, the study shows that variations in the system frequency may cause voltage problems in a weak system during restoration since the system reactance is dependent on the system frequency. Thus, large frequency variations and the unstable operation regions of turbine governors should be avoided during the restoration.

1 Introduction

1.1 Motivation

Blackouts in modern interconnected power systems are rare. However, the system may experience a disturbance or a fault combination outside the system planning criteria, which means that transmission systems operators (TSOs) cannot avoid the risk of a blackout [1]. For this reason, there is a need for robust processes to restore the system back to the normal operation. In some regions, e.g. in the European Union and in the USA, the regulation and legislation require restoration plans [2, 3]. Since electricity is extremely important in the society, the restoration should be fast. If the restoration lasts a long time, the adverse impacts of a blackout escalate rapidly.

This paper focuses on the fast restoration of a selected critical load area in a situation, where available black-start generators are located far away from the load area, and fast top-down restoration from a neighbouring power system is not possible. Top-down restoration is not possible, for example, when also in the neighbouring system has a complete blackout or a power system component along the restoration path is not available.

Fast restoration of critical load areas such as big cities and large industrial areas limits the overall consequences of the blackout since the interruption time for the critical loads is reduced [4]. While the critical load areas are being restored, the other parts of the system maybe restored in parallel at the same time. Since the overall consequences of a blackout for society depend on (i) the population in the affected area, (ii) blackout duration, (iii) economic and social consequences and (iv) the impact on health [5], it is justified to prioritise the restoration of critical load areas to limit the adverse impacts of a blackout.

1.2 Literature review

Restoration plans can be classified to top-down or bottom-up strategies [2]. In a top-down strategy, the system is re-energised using a voltage source such as a neighbouring power system, enabling fast power system restoration. In the bottom-up strategy, black-start units, i.e. synchronous generators, capable for both black start and island operation, re-energise the system step-by-step [2, 6, 7].

In the European Union, a restoration plan shall contain both a top-down and bottom-up strategies, and TSOs shall test the restoration plans if deemed necessary [2].

1.2.1 Conventional restoration: In the literature, the conventional way to perform the bottom-up restoration is to black-start selected generators. After that, transmission system segments are successively switched in. If the short-circuit current level of the island is low during the restoration, switching transients and harmonic resonances may occur. They may slow down or even prevent the restoration [2, 7–18]. Although not clearly specified, the literature implies that at first, generator voltages are raised to the nominal value, and after that the segments are connected [8–10, 15, 19].

1.2.2 Gradual voltage build-up: It is well known that a synchronous generator may energise the generator main transformer connected to the generator by gradually increasing the generator and transformer voltage before synchronising the generator and the transformer to the power system. The feature is often available in modern automatic voltage regulators (AVRs), also referred as soft energisation [20].

However, using the gradual voltage build-up in a transmission system segment comprising hundreds of kilometres of transmission lines and several transformers is hardly presented in the literature. Especially, there are not many papers proposing the detailed operational procedures, flowcharts and field-test experiences applying the gradual voltage build-up using a synchronous generator in a large transmission system segment. In addition, a CIGRE technical brochure 2015, which analyses 18 occurred large system level disturbance events, concluded that: ‘in the disturbance reports publicly available, there does not appear to be any detailed description on the restoration process’ [21].

In the gradual voltage build-up procedure, the order of switching actions is different from the conventional procedure: at

Phase	Steps during the phase
1. Select the restoration path from Station A to the critical load area	1.1. Identify possible restoration paths. 1.2. Prepare the selected restoration path for switching.
2. Start the black-start unit	2.1. Start the generator. 2.2. Set the generator to operate close to nominal grid voltage.
3. Energize local grid	3.1. Consider the risks of switching transients before switching. 3.2. Switch in transmission lines and transformers.
4. Expand the local island until short circuit current levels are sufficient for transmission system energization	4.1. Connect load to the island. 4.2 Increase the short circuit current levels of the island by connecting other generators to the system. ***Repeat steps 4.1 and 4.2 until the short circuit current levels are sufficient for transmission system energization.***
5 Energize the transmission path connecting the island to the critical load area	5.1. Energize the transformer at Station A 5.2 Energize the transmission path between the island and the critical load area. 5.3 Energize the transformer supplying the critical load area.
6. Restore the load in the critical load area	6.1. Restore the load.

Fig. 1. *Flowchart of a conventional bottom-up restoration procedure for the system shown in Fig. 2*

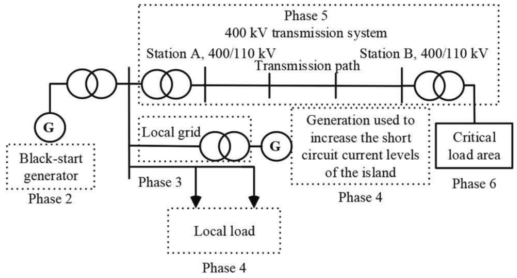

Fig. 2 *Schematic diagram of a black-start generator, a transmission system and a critical load area being restored using the conventional approach*

first, the unenergised transmission system segment is connected to the black-start generator. After that the generator excitation is initialised to a very low value, creating, e.g. ∼10% of the system voltage. Thereafter, the system voltage is gradually increased using the generator excitation. With this approach, there are no switching transients, since the transmission system components in the segment are connected without a voltage source in the system.

According to [22], the Dutch TSO has applied the gradual voltage build-up procedure (referred as soft energisation) for ∼70 km of 220 kV transmission lines and several transformers using a synchronous generator. Although the general principle for the procedure is outlined in [22], the detailed descriptions of the procedure and tests, theoretical analysis or comprehensive field-test results are not provided. Also, further analysis is needed regarding the applicability of the procedure when the harmonic resonances prevent transformer energisation during the conventional restoration.

The use of voltage-source converter (VSC) high-voltage DC (HVDC) system for gradual voltage build-up has been presented in the literature [23, 24]. In [23], the procedure has been proposed to reduce the HVDC main transformer inrush current at offshore wind power plants. In [24], the gradual voltage build-up for system restoration using a VSC HVDC system has been analysed using simulations but practical field tests are not performed and operational procedures are not presented. Furthermore, in [24], it was assumed that the neighbouring power system can support the system restoration process, which is not always the case. Also, the operational characteristics of a VSC HVDC are highly different from a synchronous generator.

1.3 Contribution of this paper

This paper proposes a detailed procedure for applying the gradual voltage build-up, for the fast bottom-up restoration of remote critical loads, which requires a long transmission path established between the loads and the black-start units. This paper provides detailed procedure flowcharts, theoretical analysis and field-test results enabling utilities to consider and further develop the proposed procedure as an alternative system restoration approach.

This paper compares the proposed procedure and conventional restoration procedures. In addition, this paper analyses the applicability of the procedure when the conventional restoration is not possible due to harmonic resonances. This paper also analyses the impact of frequency variations on managing the reactive power balance when energising a large transmission system segment.

This paper presents a proof of concept for using the gradual voltage build-up in two different successful restoration tests in two different power systems. One test was performed in the Finnish 400 kV system using a gas turbine unit connected to a ∼200 km long transmission segment. The other test was performed in the Austrian 220 kV transmission system using a hydro unit and a ∼500 km long transmission segment.

The analyses presented in this paper show that due to harmonic interaction and switching transients, the conventional restoration would not be possible for the selected grid. The results show that the restoration was successful with the gradually increased voltage. However, frequency variations may cause voltage variations in a large and weak transmission system segment.

The simulation models used in this paper were designed and validated for disturbance analysis and normal system operation. In the proposed gradual voltage build-up, the grid is very weak in the beginning and voltage fluctuations exceed the normal operational ranges. If the system operator plans to use the proposed procedure, the simulation models should be validated with field tests.

1.4 Paper organisation

This paper is organised as follows. Section 2 describes the conventional bottom-up restoration. Section 3 presents the gradual grid voltage build-up procedure and Section 4 describes the Finnish and Austrian field-test arrangements. Results are shown in Section 5 and Section 6 presents the advantages of the proposed new restoration procedure. Section 7 is for discussion and Section 8 concludes this paper.

2 Conventional bottom-up restoration

2.1 Restoration procedure

A well known conventional approach for restoring a critical load using a remote black-start generator is to start the generator, raise its terminal voltage to the nominal value and after that, switch in transformers and transmission lines (the transmission system segment) between the load and generator. Fig. 1 shows a generic flowchart for the conventional black-start process and Fig. 2 shows the power system of the restoration process.

2.2 Harmonic resonances

The risks of harmonic resonances during the conventional system restoration have been widely presented in the literatures [7–19]. The switching operations such as transformer energisation, may excite transients, which have a frequency range close to the system

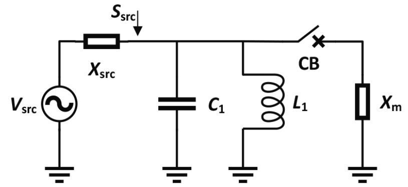

Fig. 3 *Simplified representation of a 400 kV transmission system. V_{src} is the 50 Hz voltage source and X_{src} is the purely inductive Thevenin's reactance of the source. S_{src} is the continuous short-circuit power of the source. C_1 is the shunt capacitance of the transmission line and L_1 is the inductance of the shunt reactor. The transmission line series reactance and all the resistances are neglected, to highlight the LC characteristics of the circuit. X_m is the transformer magnetising reactance. CB is open*

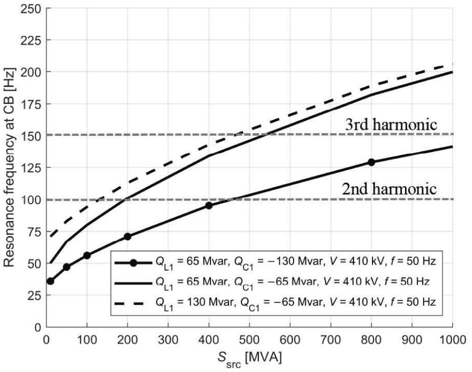

Fig. 4 *Parallel resonance frequencies of the 50 Hz system shown in Fig. 2 when the breaker CB is open. The resonance frequencies are presented as a function of the strength of the source S_{src}, the capacitive reactive power Q_{C1} generated by the capacitance C_1 and the inductive reactive Q_{L1} power generated by the inductance L_1. S_{src} is the continuous short-circuit power of the Thevenin's source shown in Fig. 2*

resonance frequency. This may lead to poorly damped transient currents and voltages, which may further lead to high voltages, magnetic saturation and trip or even damage the equipment.

Under such circumstances, the short-circuit current level of the island needs to be increased by connecting multiple generators to the island. When the short-circuit level is sufficient, large transformers and transmission lines connecting the established island system to the critical load area can be switched in [7–9]. However, this often leads to time-consuming [10] switching operations, and consequently, significantly delay the restoration.

Fig. 3 shows a simplified presentation of a 400 kV transmission system with a Thevenin's equivalent (voltage source V_{src} and purely inductive reactance X_{src}), a transmission line (presented with a shunt capacitance C_1), a shunt reactor for controlling the voltage (presented with inductance L_1) and an unenergised transformer (presented with magnetising reactance X_{m}). The transmission line series reactance and resistance are small compared with C_1 and L_1. When the circuit breaker (CB) is open, C_1 and L_1 dominate the frequency characteristics of the circuit. For this reason, the transmission line reactance and resistance are neglected.

Since the capacitive reactance X_{C1} of the line capacitance C_1 and the inductive reactance X_{L1} of L_1 are frequency dependent, the reactive powers of the devices are frequency dependent also

$$\underline{S}_{\mathrm{L1}} = 0 + \mathrm{j}Q_{\mathrm{L1}} = \mathrm{j}\frac{V^2}{X_{\mathrm{L1}}} = \mathrm{j}\frac{V^2}{2\pi f\, L_1} \tag{1}$$

$$\underline{S}_{\mathrm{C1}} = 0 - \mathrm{j}Q_{\mathrm{C1}} = -\mathrm{j}2\pi f C_1 V^2 \tag{2}$$

Fig. 4 presents the calculated parallel resonance frequencies as a function of the source strength of the 50 Hz system shown in Fig. 3 with a typical operating voltage (410 kV) when the CB is open, i.e. the transformer is not connected to the system.

Transformer energisation at nominal voltage typically excites the 2nd and 3rd harmonics [25] (100 and 150 Hz in a 50 Hz system). If the system has resonance frequencies close to these frequencies, switching in a transformer will likely cause harmonic resonances and high voltages.

Fig. 4 shows that when $S_{\mathrm{src}} = 0$ MVA, i.e. no voltage source, and $Q_{\mathrm{L1}} = Q_{\mathrm{C1}}$, the system is in parallel resonance at the 50 Hz frequency. The resonance frequency of the system increases as the system strength S_{src} increases. Therefore, as S_{src} increases, at some system strength, the system resonance frequency will cross the 100 and 150 Hz frequencies, as Fig. 4 shows. Increasing the system strength also increases the resonance frequency making the poorly damped transients by transformer energisation unlikely.

Fig. 4 also shows that increasing the absolute value of the capacitive reactive power decreases the resonance frequencies. Increasing the inductive reactive power (inductive shunt compensation) increases the resonance frequencies. Thus, the switching process may significantly change the resonance frequencies, even when the system strength does not change.

2.3 Switching process during island expansion

To avoid the problems caused by the transients and harmonic resonances, the short-circuit current level of the island should be increased by connecting other generators to the island before the transmission path connecting the island to the critical load area can be energised. During this stage, the switching process in the local distribution systems (local grid in Fig. 2) may involve coordination with different distribution system operators (DSOs) and generation companies depending on the grid topology and the ownership of the grid and the generating units.

Coordinating every step with several parties may take a long time and delay the process possibly escalating the adverse impacts of a blackout. The switching process slows down the island expansion, especially if the transmission path is long and increasing the short-circuit current level requires several generators. In Finland, for example, almost 100 DSOs exist and the generation stations suitable for island operation are owned by different utilities. The experience has shown that managing the switching processes during island expansion becomes complex and slow as the number of utilities increases.

2.4 Generator load pickup

To securely pass the possible non-linear operating range of the turbine, the load should be switched in a sufficient proportion with a pre-planned schedule. If the load fluctuates near the non-linear operating point, it is likely that the speed control of the turbine cannot maintain stable operation and frequency stability is lost.

In the Finnish system, the generators suitable for island operation are few and mostly located in the rural areas with low geographically distributed demand, making it difficult to get enough base load for the units during the island expansion and load pickup. For a typical Finnish hydro unit, equipped with a Kaplan turbine, the load pickup capability differs according to the loading level. At around 15–20% load level, the turbine speed control active power response is highly non-linear [26].

In the Austrian system, hydro power plants are typically equipped with Pelton turbines. In islanded operation, the maximum load step is up to 15% of the nominal active power of the generator depending on the control parameters.

For a gas turbine, the control response is typically very fast compared with a hydro generating unit. However, the unit characteristics should be well known to avoid an unexpected control response, when operating in an island.

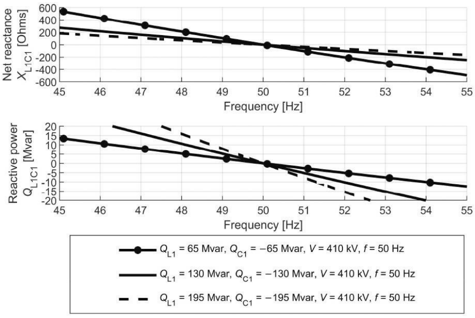

Fig. 5 *Net reactance X_{L1C1} of the parallel circuits of L_1 and C_1 in Fig. 2 and the reactive power Q_{L1C1} of the net reactance as a function of frequency with three different Q_{L1} and Q_{C1} values. Q_{L1} is the reactive power of inductances L_1 and Q_{C1} is the reactive power of capacitance C_1 at the voltage V and frequency f*

2.5 Reactive power balance during frequency variations

During system restoration, transmission lines and shunt compensation are switched into the island. Consequently, the island capacitance and inductance, seen by the generator, will change. The reactive power consumption Q of the reactance X at voltage V and the generated reactive power of the capacitance can be calculated according to the equation below:

$$Q_{L1} = j\frac{V^2}{2\pi f L_1}, \qquad Q_{C1} = -j2\pi f C_1 V^2 \tag{3}$$

The system should be continuously operated within the reactive power capability of the generators. When the shunt reactors compensate the capacitive reactance of the transmission lines, the circuit (Fig. 3) formed by L_1 and $C_1$is in resonance as given by (4). In this situation, the total reactive power Q_{L1C1} of the circuit consisting of L_1 and C_1 is zero as the positive reactive power of shunt reactors Q_{L1} compensates the negative reactive power of the transmission lines Q_{C1}

$$Q_{L1C1} = Q_{C1} + Q_{L1} = -2\pi f C_1 V^2 + \frac{V^2}{2\pi f L_1} = 0 \tag{4}$$

As the reactance is frequency dependent, the reactive power balance of the system changes when the frequency changes. Fig. 5 shows how the net reactance $X_{L1C1} = j(X_{L1} - X_{C1})$ and reactive power Q_{L1C1} of the parallel circuit of L_1 and C_1 vary as a function of system frequency. The reactive powers of L_1 and $C_1$are parameters.

Fig. 5 shows that when the magnitudes of both the inductive and capacitive reactance increase (more transmission system segments are connected, Q_{C1} and Q_{L1} increase), reactance changes caused by frequency variations also increase. Consequently, the sensitivity for the reactive power variations also increases.

2.6 Transformer sympathetic interaction

During power system restoration, the short-circuit level maybe low when long transmission lines and transformers are energised. Therefore, a risk of a transformer sympathetic interaction exists. In the sympathetic interaction, transformers that are already in operation go to saturation due to the transient inrush current of the transformer being energised. The switching transient excites a sympathetic interaction between the already connected transformers and energised transformer. The interaction significantly affects the level and duration of the transient magnetising currents [25, 27–30].

Phase	Steps during the phase
1. Select the restoration Path from Station A to the critical load area	1.1. Identify possible restoration paths. 1.2. Prepare the selected restoration path for switching.
2. Switch in transmission lines and transformers connecting Station A and critical load area at no voltage	2.1 Switch in the transformer at Station A. 2.2 Switch in the transmission path from Station A to the critical load area. 2.3 Switch in the transformer supplying the critical load area. ***Since there is no voltage in the grid, there are no switching transients.***
3. Start the seletected black-start unit	3.1. Start the generator without excitation.
4. Energize the transmission system using the controlled voltage build-up	4.1. Connect the generator to the established transmission path and to the critical load area. Now there is electrical connection between the generator and the critical load area at no voltage. 4.2. Initialize the generator excitation to as low voltage as possible. 4.3 Increase the system voltage slowly to the nominal value by increasing the generator excitation. Loads are not connected at this step.
5. Restore the load	5.1 Restore the load.

Fig. 6 *Flowchart of the proposed gradual voltage build-up procedure for the system shown in Fig. 7*

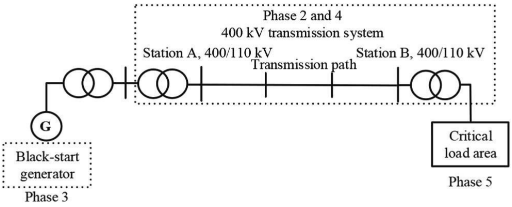

Fig. 7 *Schematic diagram of a black-start generator, a transmission system and a critical load area being restored using the gradual voltage build-up procedure*

2.7 Generator self-excitation

During the system restoration, the reactive power capacity of the black-start generator maybe small compared with the reactive power generated by the shunt capacitances of the transmission lines. An unexpected event such as a shunt reactor trip may increase the capacitive load of the generator significantly. If the capacitive load becomes too large, the generator will self-excite causing an uncontrolled voltage rise [31–33].

3 Gradual voltage build-up procedure

3.1 Description of the procedure

Fig. 6 shows a generic flowchart for the proposed gradual voltage build-up procedure for a black-start generator. The transmission system and critical load area are shown in Fig. 7.

The key difference between the proposed new process in Fig. 6 and conventional process in Fig. 1 is that the black-start generator is now started to operate at the nominal frequency (i.e. 50 Hz) without an excitation system in operation (i.e. generator voltage is

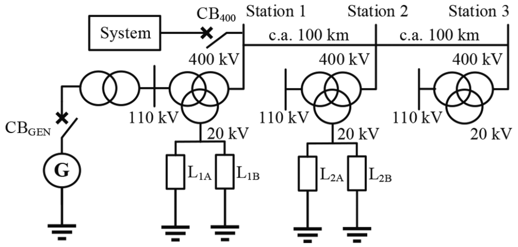

Fig. 8 *Schematic diagram of the grid with a black-start generator connected to Station 1 used for the gradual grid voltage build-up. The rating of each 400/110/20 kV transformer is 400 MVA. The rating of the generator is 175 MVA*

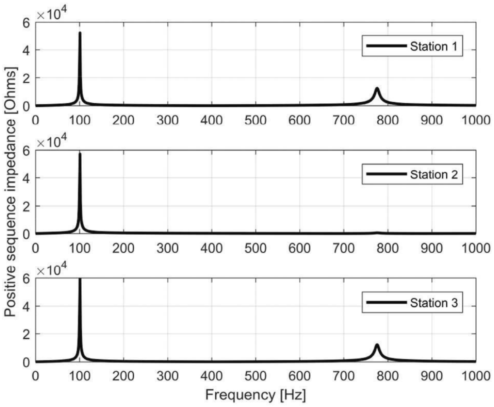

Fig. 9 *Calculated resonance frequencies of Station 1, Station 2 and Station 3 at the Finnish 400 kV system in Fig. 8 when the shunt reactors L_{1B} and L_{2B} are disconnected, the generator CB CB_{GEN} is closed and the synchronising CB CB_{400} is open*

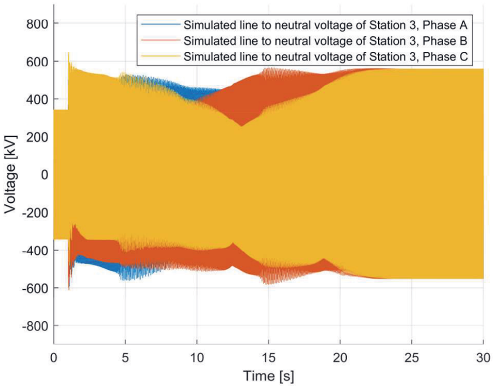

Fig. 10 *Simulated transient waveforms from the system in Fig. 8 when 400 MVA transformer at Station 3 is energised (time is 1.0 s) at close to nominal grid voltage*

very low and excited only by the generator remanence). Now, there is an electrical connection between the generator and critical load area. After that, the generator excitation is initialised, and the voltage is slowly increased to the nominal level.

3.2 Technical considerations

Gradual grid voltage build-up using generator excitation is feasible when a black-start capable generator can be connected using a high-voltage transmission path to critical load areas. The possible limitations of the black-start generator excitation system should be considered, and the unit should be capable of supplying the active and reactive powers required by the initial grid.

The active power output will be small during the initial stages. In addition, it is important that there is enough shunt compensation available to adjust the reactive power balance of the system. With too large capacitive load, the generator may start self-exciting [32].

The system protection should be carefully planned to ensure sufficient protection during the initial energisation as the normal protection arrangements at the transmission system cannot necessarily operate due to low-voltage and short-circuit current levels. Consequently, the system protection may rely on the generator protection during the early stages of the voltage build-up.

4 Field-test arrangements for testing the gradual voltage build-up procedure

4.1 Tests in the Finnish transmission system

4.1.1 Finnish test grid: Fig. 8 is a schematic presentation of the test arrangements used by the Finnish TSO Fingrid Oyj for testing the gradual voltage build-up procedure in 2018. The target of the tests was to verify the ability of the generator to connect to the system without voltage and then slowly energise the system to the nominal voltage. Load pickup was not tested, and the test did not cause disturbance or disruption for any grid user.

4.1.2 Simulated resonance characteristics of the Finnish test grid: Fig. 9 shows the calculated resonance frequencies at the 400 kV system of Station 1, Station 2 and Station 3 in the system shown in Fig. 8. Fig. 9 shows that each station has a parallel resistor–inductor–capacitor (LC) resonance spike at ∼100 Hz frequency.

Fig. 10 shows the simulated transient voltage waveform if the 400 MVA transformer at Station 3 would be energised when the grid is operating close to the nominal voltage. Fig. 11 shows the calculated harmonic components from the voltage waveforms in Fig. 10.

The simulation results in Figs. 9 and 10 have been calculated using PSCAD electromagnetic transient simulator.

Figs. 10 and 11 show that transformer energisation would cause dangerous overvoltages likely preventing the restoration and even damaging the equipment. The results show that the 2nd (100 Hz) harmonic component increases until reached the same level as the 50 Hz component.

4.1.3 Finnish test procedure: The control centre operators performed the test using the supervisory control and data acquisition remote control with the following procedure:

(i) The test grid was disconnected from the transmission system.

(ii) Shunt reactors L_{1A}, L_{1B}, L_{2A} and L_{2B} (Fig. 8) were connected to avoid the parallel resonance frequency close to 50 Hz.

(iii) The generator black started to operate at nominal speed 3000 rpm (i.e. 50 Hz) without excitation, and the CB CB_{GEN} was open.

(iv) The generator was connected to the test grid by closing the CB CB_{GEN} (Fig. 8) and the generator excitation was initialised to supply ∼10% terminal voltage.

(v) Shunt reactors L_{1B} and L_{2B} (Fig. 8) were disconnected to balance the reactive power of the system and to enable using generator reactive power capability.

(vi) The voltage build-up from 10 to 90% (at the generator voltage level) was performed in 10 min. The generator AVR was controlling the terminal voltage according to the defined ramp.

(vii) Once the voltage build-up was complete, the voltage and frequency of the system were manually adjusted using remote control.

(viii) The test grid was synchronised to the main transmission system by closing the CB CB_{400}.

(ix) Normal operation was returned in a coordinated way.

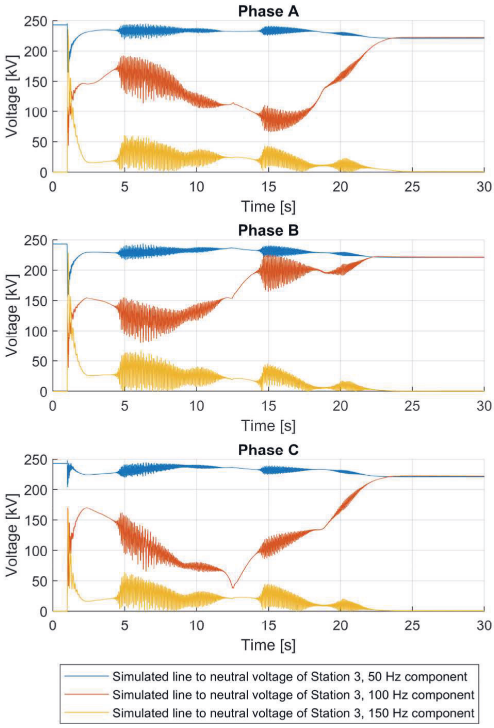

Fig. 11 *1st (50 Hz), 2nd (100 Hz) and 3rd (150 Hz) harmonic components of the simulated transient waveform in Fig. 10*

4.2 Tests in the Austrian transmission system

4.2.1 Austrian test grid: Fig. 12 shows the map of the Austrian Power Grid (APG) transmission system and test grid. The Austrian power system is a part of the Continental Europe synchronous system.

4.2.2 Austrian test procedure: The test was performed with the following procedure:

(i) The test grid was disconnected from the transmission system.
(ii) The 220 MVA pump storage power plant was black started at no load and generator was not excited.
(iii) The transmission lines and transformers were connected to the generator.
(iv) The voltage build-up was started.
(v) The pump storage power plant was loaded with ~70 MW load from the pumps.
(vi) The 300 MVA gas turbine was synchronised in the area of Vienna to the energised system.
(vii) Generators' operating points were varied to ensure proper load sharing.
(viii) The load pickup and synchronisation to the Continental Europe system were performed.
(ix) Normal operation was returned in a coordinated way.

5 Field-test results

5.1 Tests in the Finnish transmission system

Fig. 13 presents the 400 kV voltage and frequency at Station 2 shown in Fig. 8. The measurements have been recorded using a phasor measurement unit (PMU) at Station 2. Fig. 14 shows generator field voltage and current during the test.

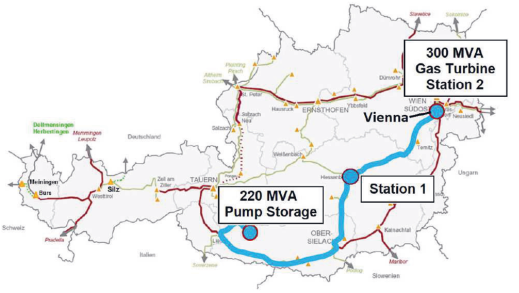

Fig. 12 *Transmission grid of the APG and the test grid during the black-start test. The test grid comprised a 220 MVA pump storage unit, a 300 MVA gas turbine unit, a ~500 km long 220 kV transmission line (marked with the blue line in this figure) and a ~15 km long 380 kV cable section*

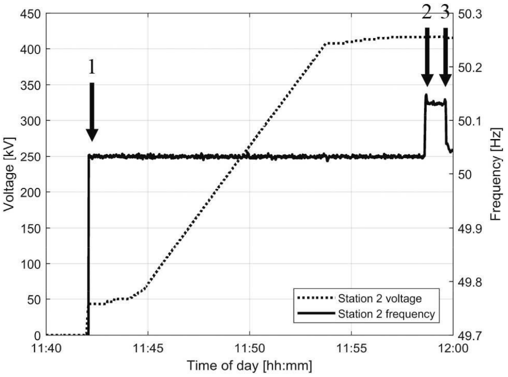

Fig. 13 *Measured voltage and frequency of the 400 kV system at Station 2 in Fig. 8 during the Finnish test. Arrow 1: excitation system initialisation, Arrow 2: frequency adjustment and Arrow 3: synchronisation*

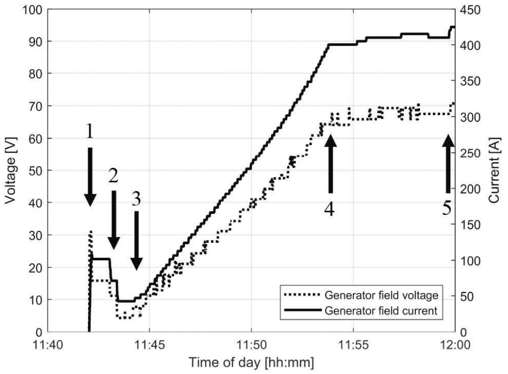

Fig. 14 *Measured field voltage and current of the generator in Fig. 8 during the Finnish test. Arrow 1: excitation system initialisation, Arrow 2: shunt reactor disconnection, Arrow 3: starting the gradual voltage build-up ramp, Arrow 4: the end of the ramp and Arrow 5: synchronisation*

The generator black-start sequence started at 11:33. At 11:42, the generator CB was closed, and the excitation of the generator was initialised to generate ~10% terminal voltage. Excitation system initialisation can be seen in Figs. 13 and 14 as the measurements become live (Arrow 1 in Figs. 13 and 14). At this point, all shunt reactors were in operation. After that, shunt reactors L_{1B} and L_{2B} were disconnected, which can be seen in Fig. 14 as step-wise changes in the generator field voltage and field current (Arrow 2 in Fig. 14).

The voltage build-up started at ~11:43 (Arrow 3 in Fig. 14) and the generator excitation started to increase the excitation as shown

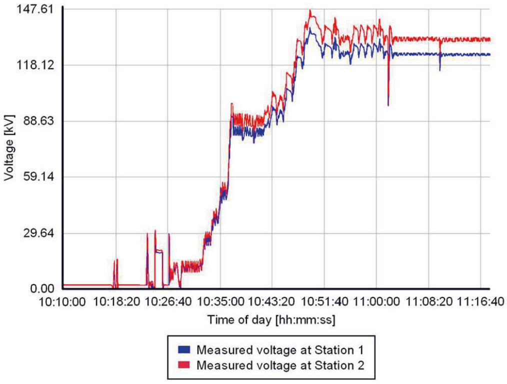

Fig. 15 *Voltage measurements from the test grid during the Austrian test. This figure shows the voltage build-up of the test grid. The voltage measurements are in the middle (Station 1, Fig. 12) and in the end (Station 2, Fig. 12) of the test grid*

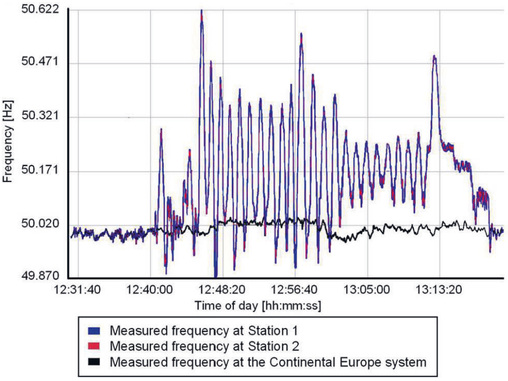

Fig. 16 *Measured frequency of the test grid at Station 1 and Station 2 in Fig. 12 and the frequency of the Continental Europe system during the Austrian test. Frequency oscillation, with ∼60 s period, in the islanded system was due to the interaction between the hydro turbine governor and gas turbine governor when both generators were loaded with ∼30 MW load from the pumps. The oscillation was damped when the power of the gas turbine was increased 10 MW*

in Figs. 13 and 14. The voltage build-up was completed at 11:54 (Arrow 4 in Fig. 14). At this point, the generator was supplying only the losses of the system and a small amount of reactive power.

At 11:58, the frequency of the test grid generator was manually increased to achieve higher frequency than the frequency of the main transmission system (Arrow 2 in Fig. 13). At 11:59, the island was successfully synchronised to the main transmission system manually using synchro-check function of the relays (Arrow 3 in Fig. 13 and Arrow 5 in Fig. 15).

The black-start command was given at 11:44. The results show that the generator voltage build-up was completed in 11:54. Thus, it took ∼20 min for the generator to black start and energise the system.

5.2 Tests in the Austrian transmission system

Fig. 15 shows the voltage measurements measured using PMUs in the middle and at the end of the test grid in the Austrian test. This figure shows that the voltage was initially 0 kV and were ramped up in ∼20 min. Between 10:35:00 and 10:43:20, the voltage build-up was paused since the hydro turbine was oscillating. After the reconfiguration of the hydro governor parameters to reduce the observed oscillation, the voltage build-up was continued. Once the voltage build-up was complete at no load, the unit was successfully loaded with the pump load.

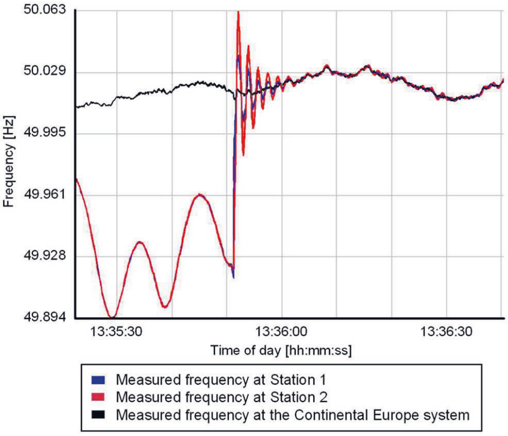

Fig. 17 *Measured frequency of the test grid at Station 1 and Station 2 in Fig. 12 and the frequency of the Continental Europe system during the Austrian test when the island was synchronised to the Continental Europe system*

Fig. 16 shows the frequency oscillations in the island after the gas turbine unit has been synchronised to the island and both units were operating at ∼30 MW load. In this case, the turbine governors of the units oscillate against each other with ∼60 s period. After the operating points of the generators were changed by increasing the power of the gas turbine by 10 MW, the oscillation disappeared. Owing to the frequency variations, the capacitive and inductive reactances of the system varied causing unexpected high voltages along the long transmission lines and reactive power variation at the generators.

Fig. 17 shows the successful synchronisation of the islanded system with the Continental Europe system. The synchronisation was initiated manually using the automatic synchro-check function of the relays.

6 Advantages of the gradual voltage build-up procedure

Concluding from the theory and results presented in this paper, the proposed procedure provides the following advantages compared with the conventional bottom-up restoration:

(i) The faster energisation of the selected transmission system segment using a single black-start generator located far away from the critical load area.

(ii) No inrush-currents and switching transients during the switching process. This is an inherent characteristic of the gradual voltage build-up procedure presented also in the literatures [20, 22, 24].

(iii) Time-consuming island expansion to increase the short-circuit current level in the island (Phase 4 in Fig. 1) can be omitted.

(iv) The faster recovery of auxiliary power supplies in the selected substations along the restoration path.

(v) Possibility to detect line faults already at very low-voltage levels by observing the voltage levels at the energised transmission system.

(vi) A black-start generator may locate in an area where the conventional restoration processes would not be possible due to lack of other generation and load. A similar observation has also been presented in [22].

7 Discussion

The tests presented in this paper show that the gradual voltage build-up procedure enables the fast energisation of a selected transmission system segment without exciting switching transients. Consequently, a remote black-start generator can be used to energise the transmission system between the unit and a load area.

In the Finnish test, a single 175 MVA generator energised ∼200 km of 400 kV transmission lines and three 400 MVA power transformers in 20 min using the procedure. In the Austrian test, a single 220 MVA generator energised ∼500 km of 220 kV transmission lines connecting the black-start generator to the load centre in 20 min.

In the Finnish test, the calculated resonance frequencies (Fig. 9), transient response (Fig. 10) and harmonic interaction (Fig. 11) in Section 4 show that the parallel resonance frequency of the test grid was ∼100 Hz, making the system prone to transients caused by the transformer energisation. The calculated overvoltages, caused by transformer switching at nominal voltage, would have tripped or even damaged the equipment, and consequently, prevented the restoration. The test results in Section 5 (Fig. 14) show that the proposed gradual voltage build-up procedure enabled energisation of the transmission path since no switching transients were excited.

The field-test results presented in this paper show that the energisation was performed in ∼20 min. This demonstrates the efficiency of the procedure for the energisation of a large transmission system segment during system restoration.

The comparison between the simulation result using the conventional restoration (Fig. 10) and test results is not possible due to the dangerous overvoltages possibly damaging the equipment in the grid. However, the simulation model used for the calculation of the results in Section 4.1.2 has been validated earlier using field-test measurements in [32].

Although harmonic resonances did not cause problems during the tests since the system voltage was increased gradually, the risk of a harmonic interaction may still be present. For this reason, the switching operations after the initial energisation require careful planning and simulations. Simulations should show that expanding the original island does not create significant transients. Special attention should be given to transformer energisation.

While expanding the island, it is recommended that generators are synchronised using the grid-side CB of the generator transformer after the generator-side CB has already been closed. This approach enables avoiding the switching transients caused by transformer energisation by closing the grid-side CB first.

The results (Figs. 5 and 16) show that frequency variations may introduce reactive power variations, and consequently, voltage problems during the restoration. In addition, small islands are inherently prone to large frequency variations and TSOs should be aware of the non-linear characteristics of the turbine governors. Since the generators typically operate at low-power levels during the early stages of the restoration, the turbine governor non-linear operating points are probable and should be passed as soon as possible. This requires enough load available in the system.

The Austrian tests (Section 5.2) revealed unstable control parameters and the challenging operation points of the turbine governor. As presented also in [34, 35], the results in this paper show the importance of the testing of restoration plans.

Since the power system restoration is a complex process, and involves exceptional system operation conditions, simulations alone cannot detect problems that might delay or even prevent the restoration. The tests are also required since the simulation models are typically linearised for normal operating conditions.

The tests should also include the synchronisation of the island to the main transmission system. In addition, the tests can be used for validating simulation models and training the control centre operators and TSO personnel.

This paper and the discussion in [22, 24] show that there are some interests that exists toward alternative system restoration methods such as the gradual voltage build-up procedure. However, there are not many papers in the literature describing the detailed operational procedures of the use of the gradual voltage build-up procedure for the energisation of a large transmission system segment using a synchronous generator and providing both the theoretical analysis of the restoration problems and the practical field-test experience presented in this paper. Generally, there are hardly any detailed descriptions of restoration procedures [21]. Thus, this paper serves as an important reference for power system restoration planning.

8 Conclusions

This paper proposes and validates, via field tests and simulations, a detailed procedure for the fast restoration of a remote load area using the gradual voltage build-up procedure in a transmission system segment comprising of hundreds of kilometres of transmission lines and several transformers. In the procedure, the switching operations are performed when there is no voltage in the transmission system segment, which will be energised. After that, the black-start generator is connected to the segment and the voltage is then gradually increased using the generator excitation.

The proposed procedure enables fast energisation while avoiding the switching transients and harmonic interaction, which are possible during conventional restoration at the nominal voltage. This paper analyses and validates the applicability of the gradual voltage build-up procedure using both theoretical analysis: simulations and field-test measurements from the Finnish 400 kV and Austrian 220 kV transmission systems.

The results show that the gradual voltage build-up procedure enables the fast (e.g. in 20 min) energisation of several hundreds of kilometres long transmission path between a black-start generator and load area, and finally, connecting the generator and the load area together.

The results show that gradual voltage build-up is beneficial, especially when the system has resonance frequencies close to the harmonics excited by transformer energisation. The gradual voltage build-up enables transmission segment energisation even when the transformer switching, using the conventional restoration approach, would have excited dangerous overvoltages in the system preventing the load restoration and possibly damaging the equipment in the grid.

Non-linear characteristics of the turbine governors should also be considered during the restoration. Since the active power levels maybe low, the governors maybe forced to operate at highly non-linear regions, which should be passed as soon as possible to avoid governor instability. Gradual voltage build-up enables fast load restoration in sufficient portions, which enables to securely pass non-linear turbine governor operating regions and to maintain the frequency stability.

Maintaining the frequency stability during restoration is important since frequency variations may lead to system reactance variations, and consequently, significant reactive power and voltage variations. This paper shows that connecting more transmission lines increases the sensitivity of the system for the reactive power variations.

The results also highlight how important it is to regularly test the restoration plans. Since blackouts and restoration actions are rare, analysed system restoration tests serve as important references for restoration planning. Transient fault recorders and PMUs are important since the system analysis requires detailed recordings from the system participating in the voltage build-up.

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PUBLICATION
II

Self-Excitation of a Synchronous Generator During Power System Restoration

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Self-excitation of a synchronous generator during power system restoration

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***Abstract*--This paper analyzes synchronous generator self-excitation during power system restoration, caused by a large capacitive load and the impact of generator voltage control on the voltage rise. The paper analyzes measurements from a recent self-excitation incident in the Finnish 400 kV transmission system, models the system using an electromagnetic transient model and a linear d-axis generator model, validates the models using the measurements and analyzes the impact of generator voltage control during self-excitation. Self-excitation is rare during normal system operation but may occur in a weak system during system restoration after a blackout. Since high voltages caused by the self-excitation may delay the restoration or even damage the equipment, self-excitation should be taken into account in restoration planning. This paper shows that the voltage controller and especially the under-excitation limiter settings of the generator have significant impact on the voltage during self-excitation. This paper also shows that details in the excitation system response influence the simulations significantly and reference measurements from the specific generator are required for detailed modeling. However, all measured incidents with digital static excitation systems are important references for simulations. In addition, special attention should be given to protection relays during the restoration.**

***Index Terms*--Power system dynamics, Power system faults, Power system modeling, Power system protection, Power system restoration, Power system simulation, Voltage control.**

NOMENCLATURE

a, *b*, *c*	Generator stator windings for phases *a*, *b* and *c*.
AVR	Automatic voltage regulator.
$\underline{E}_\mathrm{f}$	Generator internal electromotive force.
e_fd	Generator field voltage.
EMT	Electromagnetic transient.
$\vec{F}_\mathrm{a}$	Vector of magnetomotive force of stator.
$\vec{F}_\mathrm{f}$	Vector of magnetomotive force of rotor.
$\vec{F}_\mathrm{R}$	Resultant vector of $\vec{F}_\mathrm{a}$ and $\vec{F}_\mathrm{f}$.
$G(\underline{E}_\mathrm{f})$	Function describing generator excitation.
$\underline{I}$	Generator stator current phasor.
I	Generator stator current amplitude.
i_fd	Generator field current.
i_fdref	Generator field current reference.
k	Ratio of X_sys and X_d.
K_A	Gain representing power converter.
K_F	Feedback gain of field current regulator.
K_P	Proportional gain of terminal voltage regulator.
K_I	Integral gain of terminal voltage regulator.
PMU	Phasor measurement unit.
Q_G	Generator reactive power.
Q_sys	Reactive load created by the system.
T_A	Delay representing power converter.
T_F	Feedback delay of field current regulator.
T'_d0	Open-circuit d-axis transient time constant.
UEL	Under-excitation limiter.
$\underline{V}_\mathrm{t}$	Generator terminal voltage phasor.
V_t	Generator terminal voltage amplitude.
V_PImax	Maximum limit of terminal voltage regulator.
V_PImin	Minimum limit of terminal voltage regulator.
V_ref	Reference value of terminal voltage regulator.
V_Rmax	Maximum limit of field current regulator.
V_Rmin	Minimum limit of field current regulator.
V_unsat	Unsaturated generator terminal voltage amplitude.
V_{400}	Station 2 voltage amplitude at 400 kV system.
$X_{\mathrm{C}i}$	Capacitive shunt reactance of Transmission line *i*.
X_d	Direct-axis synchronous reactance.
X'_d	Direct-axis transient reactance.
$X_{\mathrm{TL}i}$	Inductive series reactance of Transmission line *i*.
$X_{\mathrm{TR}i}$	Inductive series reactance of Transformer *i*.
$X_{\mathrm{L}i}$	Inductive reactance of Shunt reactor *i*.
X_sys	Equivalent reactance of the transmission system, negative for capacitive and positive for inductive.
δ	Angle between phasors $\underline{V}_\mathrm{t}$ and $\underline{E}_\mathrm{f}$.
λ	Angle between vectors $\vec{F}_\mathrm{a}$ and $\vec{F}_\mathrm{f}$.
ϕ	Angle between phasors $\underline{V}_\mathrm{t}$ and $\underline{I}$.
ϕ_i	Angle of phasor $\underline{I}$.
ϕ_v	Angle of phasor $\underline{V}_\mathrm{t}$.

I. INTRODUCTION

SELF-EXCITATION of a synchronous generator with a capacitive load is a well-known phenomenon typically associated with weak power systems where a generator is connected to, for example, long high voltage transmission lines without sufficient amount of inductive shunt compensation. The consequence of self-excitation is excessive voltage rise, which may damage the equipment in the grid. The mechanisms of self-excitation and the factors affecting the voltage rise, especially magnetic saturation, have been widely presented in

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the literature. [1–9]

Modern power systems are typically highly meshed and interconnected, which makes the conditions for self-excitation unlikely during normal system operation. However, self-excitation may occur in a weak power system during the restoration after a major disturbance, damage the equipment and delay the restoration. Thus, utilities should take self-excitation into account in simulations, understand the risks and mitigate them in power system restoration plans. [3, 6, 10–16]

This paper presents measurements from a self-excitation incident, which occurred in the Finnish 400 kV transmission system when a synchronous generator, equipped with a static excitation system without negative field current capability, was connected to open-ended transmission lines.

Self-excitation is rare during normal power system operation. Therefore, measured incidents are important references for modeling self-excitation in restoration planning. The paper models self-excitation for power system simulations using different modeling techniques and then validates the models using field-measurements. Using the models validated with the measured incident, the paper analyzes the impact of modeling inaccuracies and voltage control characteristics of the generator voltage control on the results. In addition, the paper provides recommendations for the operation and protection of power systems during system restoration.

This paper is organized as follows. Section II introduces the theory of synchronous generator self-excitation and voltage control. After that, Section III presents the simulation models. Then Section IV presents the measured self-excitation incident and Section V validates the simulation models. Section VI analyzes the impact of generator voltage control on the results at the nominal voltage. Finally, in Section VII discusses the results and Section VIII presents the conclusions.

II. THEORY

A. Synchronous Generator with Reactive Load

In normal operation, synchronous generator load has an active component and a reactive, usually inductive component (Fig. 1a). Fig. 1b, on the other hand, is a schematic presentation of a synchronous generator connected to a purely capacitive load [9]. The figures present the rotor winding, three stator phase windings and the magnetic fluxes created by the rotor and the stator winding currents. Vector $\vec{F}_a$ shows the direction of the magnetomotive force of the stator and vector $\vec{F}_f$ shows the direction of the magnetomotive force of the rotor.

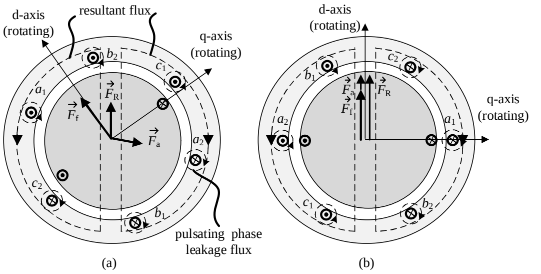
The excitation system supplies the field voltage e_{fd} and the field current i_{fd} to the generator rotor winding, creating the rotor magnetic field. Vector $\vec{F}_R$ is the resultant magnetomotive force from both the rotor and the stator as shown in Fig. 1 and given by [9]:

$$\vec{F}_R = \vec{F}_a + \vec{F}_f \quad (1)$$

Fig. 2 shows the phasor diagram for Fig. 1b, i.e. generator with the purely capacitive stator current. As shown in Fig. 2, the direction of the stator magnetic field $\vec{F}_a$ is the same with the stator current $\underline{I}$. Since there is no active load, the angle δ between internal electromotive force $\underline{E}_f$ and terminal voltage $\underline{V}_t$ is zero. The angle λ between vectors $\vec{F}_a$ and $\vec{F}_f$ can be expressed [9 Fig. 3.12]:

$$\lambda = 90° + \delta + \phi \quad (2)$$

where $\phi = \phi_v - \phi_i$, i.e. the angle between the generator terminal voltage $V_t\angle\phi_v$ and stator current $I\angle\phi_i$. The angle becomes positive with inductive stator current and negative with capacitive stator current. For purely capacitive load, $\phi = -90°$ resulting in $\lambda = 0°$, which means that the magnetic field of stator and rotor are at the same direction (Fig. 1b and Fig. 2). When the stator current is inductive, the direction of vector $\vec{F}_a$ is the opposite (Fig. 1a and Fig. 2). [9]



(a) (b)

Fig. 1. Synchronous generator magnetic flux created by the rotor current and stator currents, pulsating phase leakage fluxes around the stator windings (a_1, a_2, b_1, b_2, c_1 and c_2) and the respective magnetomotive force vectors $\vec{F}_f$ (created by the rotor current), $\vec{F}_a$ (created by the stator current), and the resulting $\vec{F}_R$, for a synchronous generator. (a) is for a generator operating with a lagging power factor and with active loading current. Modified from [9] Fig. 3.11. (b) is for a generator with a purely capacitive load. In both cases $\vec{F}_R$ and the resulting flux have been aligned to same direction.

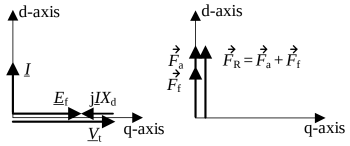


Fig. 2. The corresponding phasor diagram for Fig. 1b. Terminal voltage $\underline{V}_t$, stator current $\underline{I}$, and internal electromotive force $\underline{E}_f$ together with rotor, stator and resultant magnetic field vectors ($\vec{F}_f$, $\vec{F}_a$, and $\vec{F}_R$) for a synchronous generator which is connected to a purely capacitive load. Modified from [9] Fig. 3.12.

B. Self-Excitation

Fig. 3 presents an equivalent circuit of a synchronous generator with a purely capacitive load (X_{sys} having a negative value). Fig. 2 and (3) and (4) give the relations between the stator current $\underline{I}$, terminal voltage $\underline{V}_t$ and internal electromotive force $\underline{E}_f$, in per unit.

$$\underline{E}_f + j\underline{I}X_d = \underline{V}_t \quad (3)$$

$$\underline{I} = \frac{\underline{V}_t}{X_{sys}} \quad (4)$$

The generator has an automatic voltage regulator (AVR) for voltage control, which regulates field current i_{fd} and consequently the magnetic field $\vec{F}_{\mathrm{f}}$, and the internal electromotive force $\underline{E}_{\mathrm{f}}$, in order to maintain the terminal voltage $\underline{V}_{\mathrm{t}}$ at the desired value.

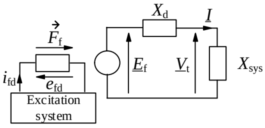


Fig. 3. A synchronous generator with a purely capacitive load (X_{sys} having a negative value) corresponding to Fig. 1b. $\vec{F}_{\mathrm{f}}$ represents the magnetomotive force of the rotor, i_{fd} the field current, e_{fd} the field voltage, $\underline{E}_{\mathrm{f}}$ the internal electromotive force and $\underline{I}$ the stator current. Modified from [9] Fig. 3.12.

If the purely capacitive stator current $\underline{I}$ increases, the stator field $\vec{F}_{\mathrm{a}}$ and resultant field $\vec{F}_{\mathrm{R}}$ also increase. In order to maintain the constant terminal voltage $\underline{V}_{\mathrm{t}}$, the generator excitation should decrease $\vec{F}_{\mathrm{R}}$ and $\vec{F}_{\mathrm{f}}$ by decreasing i_{fd}. However, i_{fd} and $\vec{F}_{\mathrm{f}}$ have a minimum limit, determined by the stability limit of the generator. If i_{fd} and consequently $\vec{F}_{\mathrm{f}}$ have already reached the minimum limit, the generator loses its ability to control $\underline{V}_{\mathrm{t}}$ if the capacitive current $\underline{I}$ continues to increase and excite $\vec{F}_{\mathrm{a}}$ resulting in uncontrolled voltage rise. [2–6, 9, 13]

C. Self-Excitation during Power System Restoration

In the bottom-up restoration, a selected generator with a black-start capability is started and then transmission lines, load and other generators are connected to the generator [11, 14]. Fig. 4 presents a power system where a single black-start capable generator is connected to high voltage transmission lines with no load, i.e. the line end of Line 2 is open-ended. The AVR controls the generator terminal voltage $\underline{V}_{\mathrm{t}}$. It is assumed, that generator armature resistance, transformer resistance and line resistance are small compared to the reactances and are for this reason neglected [2].

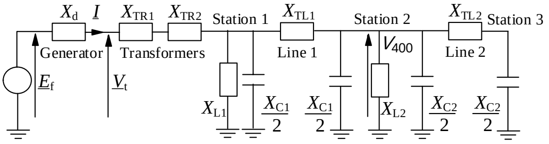


Fig. 4. A synchronous generator with a black-start capability connected to 400 kV transmission lines forming an open-ended circuit. Transmission lines are modeled with pi-equivalents. $X_{\mathrm{TL1}}, X_{\mathrm{TL2}}$ are transmission line series inductive reactances, X_{C1} and X_{C2} are (negative) line capacitive shunt reactances. X_{L1} and X_{L2} are shunt reactor reactances, X_{d} the generator direct-axis synchronous reactance, X_{TR1} the reactance of the generator step-up transformer to 110 kV system and X_{TR2} the reactance of the main transformer from 110 kV to 400 kV system. Voltage V_{400} is the voltage amplitude at Station 2.

The generator in Fig. 4 sees the whole transmission system at its terminals as an equivalent reactance X_{sys} as shown in Fig. 3. During system restoration, unloaded transmission lines increase the system capacitance and shunt reactors will increase system inductance seen by the generator. In order to avoid self-excitation the capacitive load of the generator, i.e. the system reactance, should be within the limits that the generator is able to control. If the load becomes too capacitive, for example due to a shunt reactor trip, the generator starts self-excite and the system may become unstable. [2–5, 13, 14]

D. Voltage Control and Reactive Power Balance

The reactive power balance of the system in Fig. 4 is the result of the capacitive and inductive components of the system. If the generator is on terminal voltage control, it regulates voltage V_{t} and supplies the total reactive power demand Q_{sys} of the system, determined by the system reactance X_{sys}:

$$Q_{\mathrm{G}} = Q_{\mathrm{sys}} \tag{5}$$

where Q_{G} is the reactive power output of the generator.

A weak power system is sensitive to changes in parameters affecting the reactive power balance. If the only generator or any other component continuously controlling the voltage is not capable of providing the reactive power needed by the system, the risk is that the voltage stability of the system will be lost. Low voltages may result in tripping of loads and other equipment risking the stability of the system and delaying restoration. High voltages, on the other hand, may even cause equipment damage, preventing the restoration. [6, 12–16]

If the power system has only a few generators, the voltage stability of the system is sensitive to the ability of the generators to control the voltage. AVRs typically have both static and dynamic limiters such as under-excitation limiter (UEL), which ensures the sufficient generator rotor field under different circumstances affecting the generator voltage control and reactive power capabilities. [6, 12–16] In addition, negative field current capability significantly affects the voltage control characteristics of the generator. [13, 14]. However, not all the generators in the Finnish power system have this capability.

III. MODELING THE POWER SYSTEM

A. Description of the Power System

The modeled power system is presented in Fig. 4. The system has one 175 MVA synchronous generator with a step-up transformer to 110 kV system and a main transformer to 400 kV system, and two circa 100 km long 400 kV transmission lines in series between Stations 1, 2 and 3. The shunt capacitances of the transmission lines were validated using measurements from SCADA and phasor measurements units (PMU). The rated reactive power of each shunt reactor is 65 Mvar.

The system shown in Fig. 4 can be represented using the equivalent representation shown in Fig. 3. In [2], the ratio k has been used to describe the relation between X_{sys} and X_{d}:

$$k = \frac{X_{\mathrm{sys}}}{X_{\mathrm{d}}} \tag{6}$$

For a capacitive system with negative X_{sys}, k is always negative as X_{d} is always positive. When the system capacitance increases, the absolute value of (negative) system reactance decreases. Table I shows the values of k for the system shown in Fig. 4 with shunt reactor X_{L2} connected and disconnected using the equivalent representation shown in Fig. 3.

As Table I shows, when the shunt reactor X_{L2} at Station 2 is disconnected, the absolute values of the system reactance and the generator synchronous reactance are almost equal. As presented in [2, 14], this condition makes the system prone to direct-axis resonance and generator self-excitation.

TABLE I
RATIO OF SYSTEM REACTANCE AND GENERATOR REACTANCE

Topology of the system shown in Fig. 4.	Ratio k expressed using equivalent presentation in Fig. 3 and (6).
All transmission components in Fig. 4 are in operation.	$k = \frac{X_{\mathrm{sys}}}{X_{\mathrm{d}}} = \frac{-17.0\ \mathrm{p.u.}}{2.12\ \mathrm{p.u.}} = -8.0$
The shunt reactor at Station 2 (65 Mvar, reactance X_{L2}) in Fig. 4 is disconnected.	$k = \frac{X_{\mathrm{sys}}}{X_{\mathrm{d}}} = \frac{-2.16\ \mathrm{p.u.}}{2.12\ \mathrm{p.u.}} = -1.02$

B. Linear Direct-Axis Model with Saturation Characteristics

The linear direct-axis model (d-axis model) used in this paper is presented in [2] where it was used to study generator self-excitation using analogue computation methods. The model assumes linear d-axis characteristics of the synchronous generator [2]:

$$V_{\mathrm{t}} = \frac{1}{T'_{\mathrm{d0}}} \int [G(E_{\mathrm{f}}) - X_{\mathrm{d}} I - V_{\mathrm{t}}] dt - X'_{\mathrm{d}} I \qquad (7)$$

where $G(E_{\mathrm{f}})$ is the function describing the generator excitation i.e. the varying internal electromotive force affected by the generator excitation system, X'_{d} is the transient d-axis reactance of the generator, T'_{d0} is the open-circuit d-axis transient time constant and I is the stator current. As presented in [2] and shown in Fig. 5, generator magnetic saturation is taken into account using a function generator which implements the open-circuit saturation characteristics provided by the manufacturer.

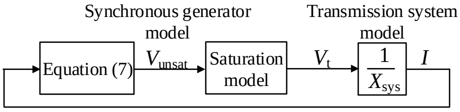


Fig. 5. The linear d-axis model with a non-linear magnetic saturation model as presented in [2]. V_{unsat} is the unsaturated generator terminal voltage, V_{t} is the generator terminal voltage taking into account magnetic saturation, X_{sys} is the transmission system reactance and I is the amplitude of the stator current.

The model enables running several simulations in a short period of time but neglects transient phenomena such as transformer saturation, inrush currents and harmonic resonances, which may have significant impacts during restoration [13].

C. Non-Linear Electromagnetic Transient Model (EMT)

The electromagnetic transient (EMT) model was build using PSCAD simulation software. The model was built using the standard PSCAD synchronous generator component and a static excitation system model. The magnetic saturation of the generator and transformers were modeled using the data provided by the generator manufacturer. The generator excitation system and AVR were modeled in detail using the block diagrams and parameters obtained from the manufacturer. Transmission lines were modeled using the frequency dependent model, for which PSCAD calculates parameters from the line geometry and conductor data. Shunt reactors were modeled as passive inductive components. Simulations with this model are significantly slower than with the linear d-axis model but this model makes it possible to also model transformer magnetic saturation, harmonic resonances and switching transients in the system.

IV. MEASURED SELF-EXCITATION INCIDENT

Fig. 6 shows measurements from the self-excitation incident, which occurred during a black-start test. The generator was connected to two series-connected 400 kV transmission lines, with an open end, as shown in Fig. 4. In the test, unenergized open-ended transmission lines, transformers, two shunt reactors and the generator were connected before the excitation system of the generator was started and the initial excitation field was applied to the generator. After the excitation was started, the terminal voltage of the generator was initialized to 10 % of the rated value and the generator AVR was regulating the terminal voltage. As shown in Table I, the value of k was −8.0 in this topology. This approach enabled avoiding switching transients, which would have occurred if the lines and transformers were switched into the system at nominal voltage.

After the initialization, the purpose was to slowly increase the voltage of 400 kV system to its nominal value using the generator voltage control. However, before starting the voltage ramp, the shunt reactor X_{L2} at Station 2 in Fig. 4 disconnected due to an unexpected action of the compensated reactor unbalance protection relay. This specific relay type uses a fixed current compensation tuned at the rated voltage and current. In this event, the voltage was low and the current unbalance was small but the fixed compensation setting caused the relay to detect an unbalance and trip the reactor.

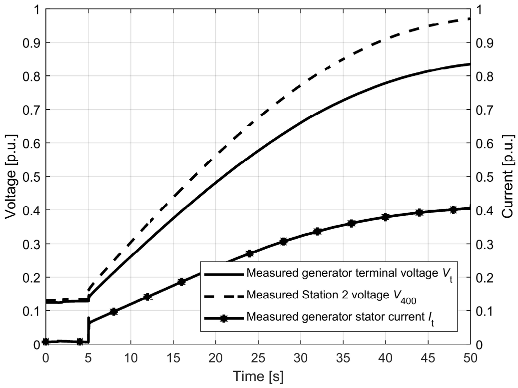


Fig. 6. Measured voltage V_{t} at generator terminals (1 p.u. = 15.75 kV), stator current I_{t} at generator terminals (1 p.u. = 6400 A) and V_{400} at Station 2 400 kV system (1 p.u. = 400 kV) in Fig. 4 during self-excitation. The shunt reactor trip occurs when time is 5 s.

The reactor trip increased the capacitive load of the generator significantly and changed the value of k from −8.0 to −1.02 as shown in Table I. The measurements indicate that generator excitation reached its minimum limit and was not able to control generator terminal voltage. Since the capacitive stator current continued to excite the generator, the system experienced an uncontrolled voltage rise as shown by the measurements in Fig. 6. Due to the Ferranti effect, the voltage is higher at Station 2 than at the generator terminals.

Since the self-excitation started when the initial voltage of the generator was low, the magnetic saturation [2, 8] did not significantly influence the voltage at the beginning of the incident. Thus, the measured data provides reference for modeling self-excitation using simulation software without saturation characteristics.

V. VALIDATION OF SIMULATION MODELS

A. The Simulation Models

The two simulation models presented in Section III were validated using the data measured in the self-excitation event presented in Section IV. The validation was performed analyzing the response of the models to the trip of 65 Mvar shunt reactor X_{L2} shown in Fig. 4.

The EMT model includes the models of the transmission lines in detail and it is possible to trip the reactor in the model.

However, in the linear d-axis model shown in Fig. 5, the reactor trip was performed by changing the system reactance X_{sys}, which changed k from −8.0 to −1.02 as shown in Table I.

B. Constant Excitation

Fig. 7 show the simulated generator voltage during the self-excitation due to the shunt reactor trip when the field voltage e_{fd} of the generator was constant in the simulations. The simulations were based on the assumption that the generator excitation was initially operating close to the minimum excitation limit since the AVR was already regulating the terminal voltage at the circa 10 %, which corresponds to the minimum terminal voltage the excitation system can generate.

The results in Fig. 7 show that both the linear d-axis model and the EMT model provide similar results. Similar to measurements, the simulations show a 10 % step-wise increase in the terminal voltage immediately after the shunt reactor trip.

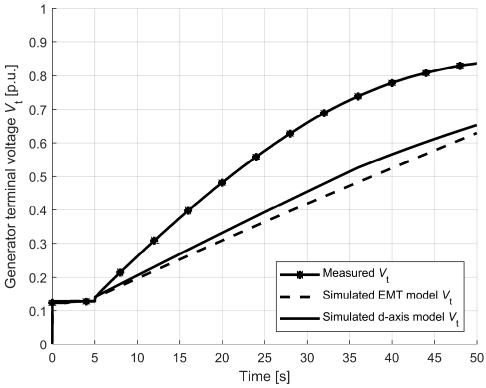


Fig. 7. Measured and simulated voltage rise at generator terminals during the self-excitation incident. The shunt reactor trip occurs when time is 5 s. Generator field voltage remains constant at circa 10 % during the simulation.

The simulation results show smaller voltage rise during self-excitation compared to the measurements. In addition, the measurement shows a non-linear voltage profile meanwhile both simulation results show a linear voltage profile.

C. Excitation System Measurements

Fig. 8 and Fig. 9 show the generator field voltage and current during the self-excitation, measured from the terminals of the static excitation system. The measurements were filtered using the moving average method with a 100 ms time window.

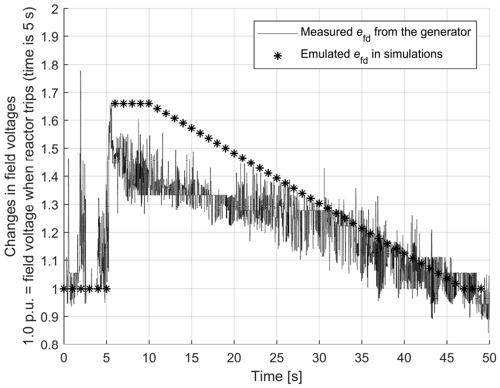


Fig. 8. Measured and emulated generator field voltage during the self-excitation incident. The figure presents relative changes in the voltages in such way that 1 p.u. = 18 V, i.e. the field voltage at the exact time when the shunt reactor trips (time is 5 s). Note that the rated field voltage is circa 240 V, i.e. the observed change is small compared to the rated field voltage.

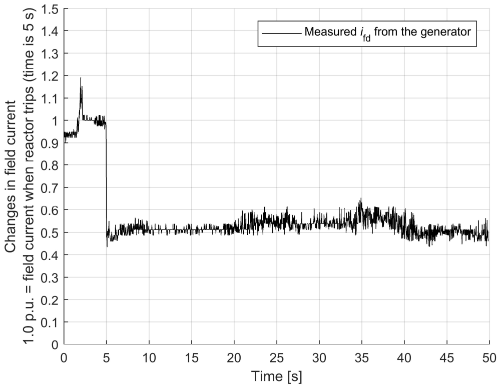


Fig. 9. Measured field current during the self-excitation incident. The figure presents relative changes in the current in such way that 1 p.u. = 40 A, i.e. the field current at the exact time when the shunt reactor trips (time is 5 s). Note that the rated field current is circa 1200 A, i.e. the observed change is small compared to the rated field current.

D. Emulating the Measured Excitation-Response

According to the measurements (Fig. 8 and Fig. 9), the field voltage increased 65 %, from 18 V to 30 V, immediately after the reactor trip. Similarly, the field current suddenly decreased 50 % from 40 A to 20 A. Fig. 9 indicate that 20 A could be the minimum field current limit of the excitation. Compared with the rated values of the excitation system (rated i_{fd} = 1200 A, rated e_{fd} = 240 V), the values and the changes are small.

Since the measurements show an increase in the field voltage, the assumption of a constant excitation was not valid. The measurements show the following instantaneous changes immediately after the shunt reactor trips.

1. Minor step-wise increase followed by a significant increase in the stator voltage (Fig. 6).
2. Minor step-wise increase followed by a significant increase in the capacitive stator current (Fig. 6).
3. Minor step-wise increase followed by a slow decrease in the field voltage (Fig. 8).
4. Minor step-wise decrease in the field current (Fig. 9).

Due to the reactor trip, X_{sys} changes from $-8X_{\mathrm{d}}$ to $-1.02X_{\mathrm{d}}$ (Table I) and the capacitive stator current and stator voltage increase (Fig. 3). Consequently, the internal electromotive force of the generator ($\underline{E}_{\mathrm{f}}$ in Fig. 3) also increases. Because of the armature reaction of the capacitive stator current, the field voltage e_{fd} changes as shown in Fig. 8.

The excitation system is shown in Fig. 10. The system controls the field voltage and current in order to maintain the stator voltage V_{t} at the circa 10 % reference value. Since the stator voltage increases above the reference value, the voltage regulator decreases the field current reference i_{fdref} in order to limit the voltage rise, shown in Fig. 9.

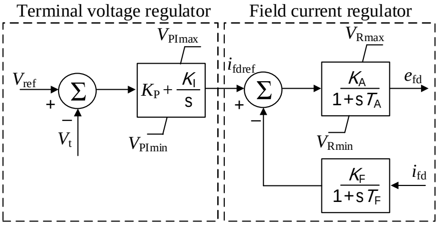


Fig. 10. The simplified representation of the IEEE ST8C [17] static excitation system model with a terminal voltage regulator and a field current regulator in cascade. V_{ref} is the terminal voltage reference, V_{t} is the measured terminal voltage, K_{P} and K_{I} are the proportional and integral gains of the voltage regulator, i_{fd} is the measured generator field current, i_{fdref} is the field current reference and e_{fd} the generator field voltage. Gain K_{a} and delay T_{a} represent the power converters and gain K_{F} and delay T_{F} represent the field current feedback.

Fig. 11 shows the simulated voltage profiles when the measured field voltage profile (Fig. 8) was emulated in the simulation models using the signal in Fig. 8.

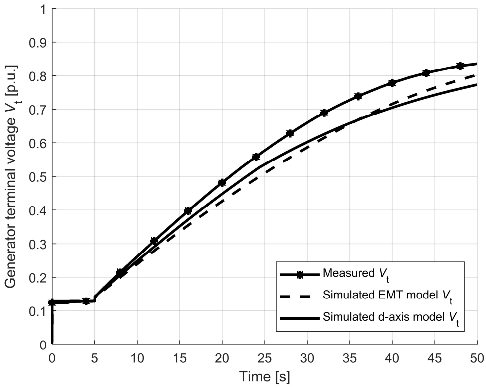


Fig. 11. Measured and simulated voltage rise at generator terminals during the self-excitation incident. The shunt reactor trips when time is 5 s. The emulated signal (Fig. 8) was added to the field voltage in both simulation models using a function generator in order to emulate the measured field voltage rise.

In the EMT model, the emulation signal was added to the output of the excitation system model. In the linear d-axis model, the signal was added to excitation function $G(E_{\mathrm{f}})$.

The results in Fig. 11 show that after the measured minor step-wise field voltage profile was emulated in the simulation models using the emulated voltage profile shown in Fig. 8, the simulated voltage profiles became close to the measured voltage profile.

E. Sensitivity of the System to Reactance Variations

In order to understand the sensitivity of the system to modeling inaccuracies in system and generator reactances, the ratio k was varied from −1.04 to −1.0. The study was performed using the linear d-axis model. The results are shown in Fig. 12.

The results show that varying k from −1.04 to −1.0 increases the voltage from 0.74 p.u. to 0.81 p.u., when time is 50 s, i.e. 45 s after the reactor trips. This indicates that even small variations in system or generator reactance may lead to large variations in simulations results.

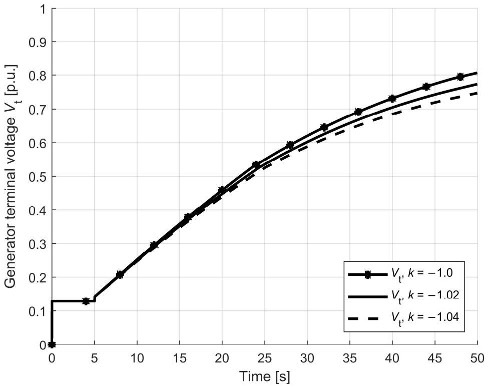


Fig. 12. The impact of system reactance X_{sys} on the voltage rise during self-excitation. The reactor trips and the self-excitation starts when time is 5 s.

F. Sensitivity of the System to Excitation System Parameters

In order to understand the sensitivity of the system to the excitation system parameters, simulations with three different minimum field current reference values (V_{PImin} in Fig. 10) were performed. The simulation parameters are shown in Table II. The value of k was −1.02 in the simulations.

TABLE II
EXCITATION SYSTEM PARAMETERS IN THE SENSITIVITY ANALYSIS

Estimated parameters of the field current regulator shown in Fig. 10. $K_{\mathrm{A}} = 2.0$, $T_{\mathrm{A}} = 0.002$ s, $K_{\mathrm{F}} = 1.0$, $T_{\mathrm{F}} = 0.001$ s
Studied values of V_{PImin}: $V_{\mathrm{PImin}} = 0.08$ p.u., $V_{\mathrm{PImin}} = 0.10$ p.u. and $V_{\mathrm{PImin}} = 0.12$ p.u.

The study was performed using the EMT model and the results are shown in Fig. 13.

The results show that varying V_{PImin} from 0.08 p.u. to 0.12 p.u. increases the voltage and the end of simulation from 0.56 p.u. to 0.72 p.u. This indicates that the system is also sensitive to excitation system parameters and small variations may lead to large variations in simulations results.

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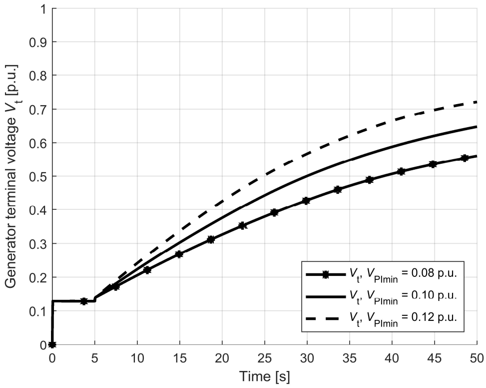

Fig. 13. The impact of the minimum field current reference (V_{PImin}) of the excitation system on the voltage rise during self-excitation. The reactor trips and the self-excitation starts when time is 5 s.

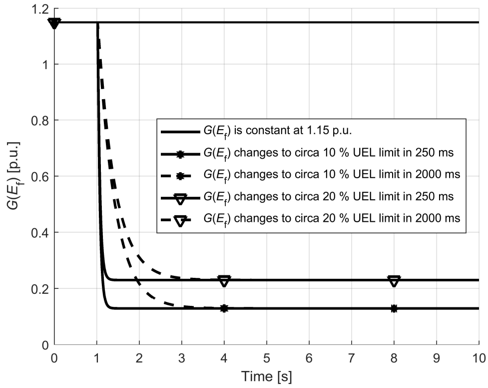

Fig. 14. Variation of excitation function $G(E_f)$ which was used as an input in the linear d-axis model: constant excitation and UEL limit settings (circa 10 % and 20 %) and response times (250 ms and 2000 ms). Value $G(E_f)$ = 1.15 p.u. corresponds to excitation which creates 1.0 p.u. terminal voltage V_t.

VI. SIMULATION OF SELF-EXCITATION AT NOMINAL VOLTAGE

A. *Impact of Under-Excitation Limiter Settings*

If self-excitation occurs when the transmission system is already operating at its nominal voltage (400 kV), the AVRs will react to the voltage rise by decreasing generator excitation if the voltage control is enabled. The impact of AVR response on the voltage rise in the system described in Section III was studied by simulating the trip of the 65 Mvar shunt reactor X_{L2} with different UEL settings values shown in Fig. 14 and with different X_{sys} values and consequently different values of k.

The simulation was performed using the linear d-axis model. The model was considered sufficient since simulations analyze the excitation system response, not transient phenomena, and the model is fast to run. The simple model takes into account the generator saturation and the comparison in Section V did not show significant difference between the models.

Fig. 15 shows the results with the constant excitation. Since the excitation is constant, the UEL setting does not influence the results.

Fig. 16 and Fig. 17 show the results when the AVR is on voltage control with different UEL settings. Since the AVR reacts to the terminal voltage, the UEL setting has impact on the results as Fig. 16 shows. The results show that with constant excitation the voltage rises over 1.1 p.u. in a few seconds after the self-excitation starts. However, the results in Fig. 16 and Fig. 17 show that if the AVR is enabled and allow under-excitation, it may significantly limit the voltage rise.

The results in Fig. 16 and Fig. 17 show that the UEL setting value is more significant than the response time of the UEL. When the UEL setting is 10 % and the response time is 2000 ms, the generator is able to recover the voltage when k is -1.02. If the UEL setting is 20 %, the generator is not be able to recover the voltage when k is -1.02, even if with 250 ms response time.

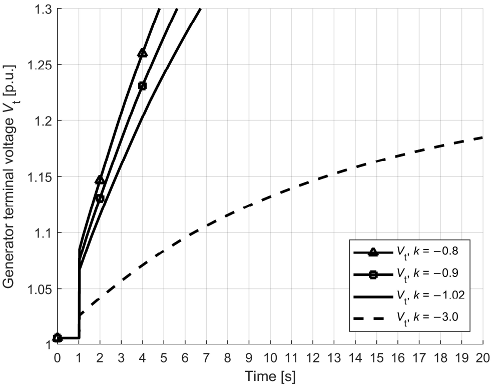

Fig. 15. Simulated voltage profile during the self-excitation, initial voltage 1.0 p.u. Excitation term $G(E_f)$ is constant 1.15 p.u. as shown in Fig 14.

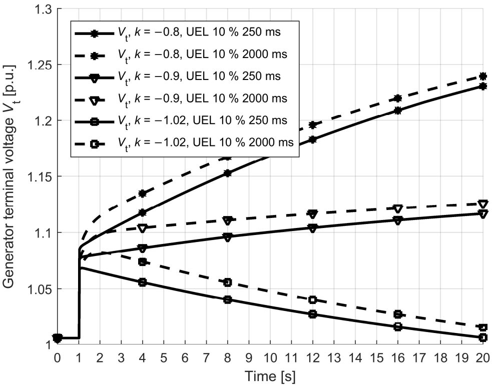

Fig. 16. Simulated voltage profiles during the self-excitation with the initial voltage of 1.0 p.u. Excitation term $G(E_f)$ changes from 1.15 p.u. initial value circa 0.1 p.u. value which corresponds to the 10 % UEL setting with different response times as shown in Fig. 14.

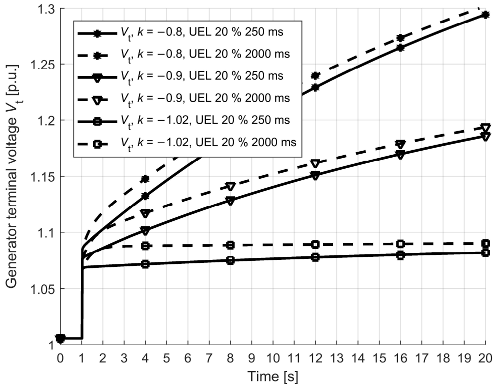

Fig. 17. Simulated voltage profiles during the self-excitation with the initial voltage of 1.0 p.u. Excitation term $G(E_f)$ changes from 1.15 p.u. initial value circa 0.2 p.u. value which corresponds to the 20 % UEL setting with different response times as shown in Fig. 14.

B. *Impact of Negative Field Current Capability*

Many static excitation systems allow negative field forcing, i.e. the system is able to supply negative field voltage in order to reduce the field of the generator. However, most static excitation systems do not supply negative field current. [17]

The impact of the negative field current capability of the excitation system on the voltage rise during self-excitation was studied with two values of excitation system minimum field current reference (V_{PImin} shown in Fig. 10). First, the reference simulation without negative field current capability was performed using value V_{PImin} = 0.15 p.u. After that, the simulation was repeated with negative field current capability i.e. $V_{\mathrm{PImin}} = -0.15$ p.u. The study was performed using the EMT model. In the simulation, the voltage before self-excitation is 1 p.u. and k is −0.8.

Fig. 18 shows the voltage profile during self-excitation. Respectively, Fig. 19 shows the generator field current and field voltage during self-excitation.

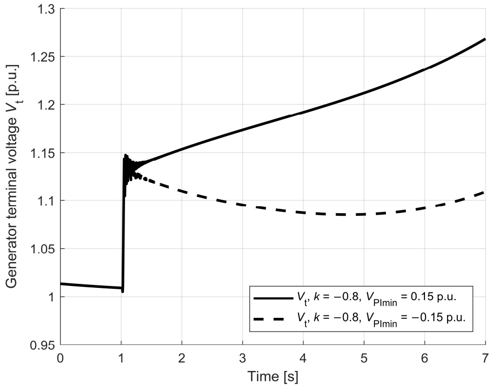

Fig. 18. Simulated EMT model voltage profiles during the self-excitation with the negative field current capability ($V_{\mathrm{PImin}} = -0.15$) and without the negative field current capability ($V_{\mathrm{PImin}} = 0.15$).

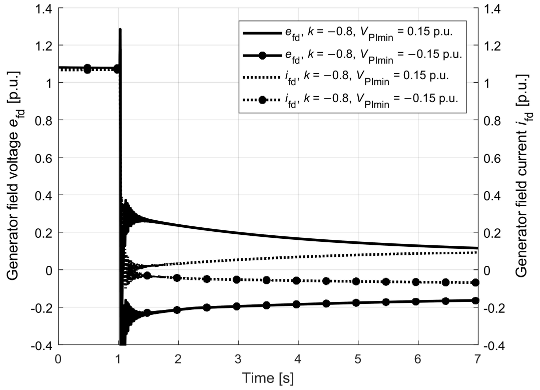

Fig. 19. Simulated EMT model generator field voltage and field current during the self-excitation with the negative field current capability ($V_{\mathrm{PImin}} = -0.15$) and without the negative field current capability ($V_{\mathrm{PImin}} = 0.15$).

The results show that the negative field current improves the ability of the generator to limit the voltage rise temporarily in a system with one generator. The negative field current causes the rotor field to change the direction by 180°. Since the generator is the only voltage source in the system, also the phase of the stator voltage changes by 180°. Since the generator remains connected to the capacitive load, the voltage rise starts again after a few seconds.

VII. DISCUSSION

The self-excitation incident that occurred in the Finnish 400 kV transmission system shows that self-excitation is possible during the power system restoration. Measured analyzed incidents are important references for restoration planning and modeling. Although the problems related to self-excitation have been presented in literature [2, 3, 6, 10–16], real, documented and analyzed self-excitation incidents in high voltage transmission systems are not many.

Uncontrolled voltage rise may lead to component trips, delay the restoration, and even damage the equipment in the grid. Therefore, it would be beneficial for transmission system operators and utilities to identify the problem and analyze the risk of self-excitation in their restoration strategies. [10, 13, 14]

Similar to the discussion in [18], the incident presented in the paper shows the importance of the robust performance of protection relays during restoration. In this paper, the root-cause for the large capacitive load to the generator and the self-excitation was an unintentional shunt reactor trip caused by the compensated reactor unbalance relay. The fixed current compensation setting was set to compensate the natural unbalance of the reactor phase currents at the rated voltage and current. When the voltage was low, the current unbalance was small but the fixed compensation setting caused the relay to detect an unbalance and trip the reactor.

During power system restoration, exceptional voltages and currents may occur, which should be considered in relay configuration and testing practices. In addition, over-voltage relays should be used to automatically connect shunt reactors in case of voltage rise. Under-voltage protection, which

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disconnects reactors require careful coordination since voltage swings could trip reactors and trigger the self-excitation.

The measurements and simulations of the paper show that self-excitation simulations are sensitive to modeling inaccuracies in both generator excitation and transmission systems. The results presented in Section V shows that even small variations in generator or transmission system reactance or excitation system parameters may lead to significant variations in simulation results. Varying k from −1.04 to −1.0 increases the voltage from 0.74 p.u. to 0.81 p.u. at the end of the simulation. Similarly, varying the excitation system minimum field current reference (Table II) also significantly affects the simulation results (Fig. 13). This is in line with the literature, where modeling inaccuracies, such as generator and transmission system reactances, magnetic saturation, generator excitation systems and its characteristics, especially negative field current capability, have been presented factors affecting the voltage rise. [2, 8, 14]

In this paper, the self-excitation occurred during the black-start test when the voltage of the system was low. Therefore, magnetic saturation did not occur when the self-excitation started and the incident provides data for analyzing the unsaturated characteristics of the system.

The analysis using a real measured self-excitation incident and simulations in Section V broadens the understanding of the significant impact of the generator excitation characteristics on the excessive voltage rise during generator self-excitation. The measured changes in the generator field voltage (Fig. 8) and field current (Fig. 9) during self-excitation were small but had a significant impact on the results in simulations (Fig 7. and Fig. 11). The measured changes boosted the voltage at the end of the simulation from 0.65 p.u. (Fig. 7) to 0.78 p.u.

In this study, the interaction between the generator and excitation systems shown in Fig. 8 and Fig 9 could not be repeated with the EMT models. Instead, modeling the interaction required the use of a function generator in the simulations. This indicates that the modeling of the excitation system response during self-excitation is challenging and may be impossible, without measurements from the specific generator and excitation system under study. Thus, sufficient safe margins are important when using the simulation results in the restoration planning.

The analysis in Section VI shows that during the restoration the generator AVRs should be controlling the terminal voltage to support the system in case of self-excitation. Especially, the UEL setting value significantly affects the ability of the generator to limit the excessive voltage rise during self-excitation.

As presented in [21], too high UEL settings create an unnecessary limit on the reactive power capability of the generator. On the other hand, too low UEL setting values may risk the stability of the generator due to reduction in synchronizing torque and damping torque [21]. Thus, UEL settings should maximize the generator's ability to absorb reactive power from the system in order to limit the excessive voltage rise during self-excitation, however, without risking the stability.

As the self-excitation incident and the simulations in this paper show, when the system is highly capacitive compared to the generator rating, even very low UEL settings are not able to prevent self-excitation and voltage rise.

Section VI shows that the negative field current capability increases the ability of the generator to limit the voltage rise only temporarily in a single machine system and the voltage rise starts again after a few seconds. Since negative field current has an adverse impact on the stability of the generator, the use of the negative field current shall be carefully considered. However, analyzing the impact of negative field current in a specific use case or application requires more analysis.

Similar to other reported field-tests such as [19, 20], this paper shows the importance of the systematic testing of substation equipment, protection relays and generator controls considering system restoration. Utilities should also consider using PMU measurements and transient fault recorders in substations participating in the initial stages in the restoration.

VIII. CONCLUSIONS

This paper analyzes a synchronous generator self-excitation during power system restoration, caused by the capacitive load, and then broadens the analysis to the impact of generator voltage control on the excessive voltage rise. If the self-excitation and uncontrolled voltage rise occur during the system restoration, it may damage the equipment and delay or even prevent system restoration.

The study is based on a measured self-excitation incident that occurred during a black-start test in the Finnish 400 kV transmission system due to an unexpected trip of a shunt reactor by unbalance current protection. Analyzed self-excitation incidents are important references for restoration planning.

The results show that simulations of the interaction between the generator and its digital static excitation system during self-excitation require reference measurements from the specific units. The results show that small variations in generator and transmission system reactance or excitation system parameters may have significant impact on the simulation results. Thus, sufficient safe margins are important when applying the simulation results in the restoration plans. Special attention shall be given to the configuration and testing of protection relays and generator controls.

The results show that the UEL has a significant impact on the voltage rise during self-excitation. Especially, the UEL final limit setting is more significant than the response time. Thus, UELs should be set to allow as low excitation as possible without risking the stability of the generator. However, when the system is highly capacitive compared to the generator rating, even very low UEL settings are not able to prevent self-excitation and voltage rise.

The results indicate that the generators should be on terminal voltage control during system restoration in order to support the system if unexpected self-excitations happen. The results also show that the negative field current capability of the excitation system only temporarily improves the ability of the generator to limit voltage rise during self-excitation in a single machine system.

Future work is recommended regarding restoration related field-testing, especially black-start units, digital excitation systems, negative field current capability and protection relays. It would be beneficial to equip the stations, participating in the early stages if the restoration, with fault recorders and PMUs.

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IX. BIOGRAPHIES

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PUBLICATION
III

Ferroresonance and subsequent sustained parallel resonance occurrence during power system restoration: analyses for system operation

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Ferroresonance and subsequent sustained parallel resonance occurrence during power system restoration: analyses for system operation

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Abstract

This paper analyses ferroresonance and subsequent sustained parallel resonance that occurred during Finnish power system restoration tests and studies how to prevent those with operational actions. The resonances may cause high voltages damaging the grid equipment. The resonance occurred on a disconnected circuit comprising a transformer and shunt compensated transmission line. The circuit was supplied through capacitive coupling by a parallel connected transmission line. The study is based on field measurements and simulations with validated models. The study shows that the sustained resonance can occur if the resonance frequency of the studied disconnected transmission system segment is within about 2 Hz of the system operating frequency. Also, the study shows that changing the resonance frequency significantly influences the resonance occurrence and even attenuates already triggered resonance. Thus, the restoration planning should study the resonance frequencies of the segments being energised and how to change the resonance frequency with operational actions.

1. Introduction

1.1 Motivation

Operating conditions during power system restoration after a blackout are significantly different from the conditions during normal system operation. Phenomena such as ferroresonance, generator self-excitation and harmonic resonance, seldom encountered during normal system operation, may occur during restoration [1−5]. Since the actual restoration actions are rare, there are little practical experiences in managing these phenomena, which system operators could use as a reference for restoration planning. Therefore, preparing for the system restoration and its possible problems should be done beforehand with simulations, analysis of the operational actions and field tests validating the models and the restoration plans.

This paper analyses ferroresonance and a subsequent sustained parallel resonance incident that occurred in 2018 during power system restoration field-tests in the Finnish 400 kV transmission system. The paper also investigates how to prevent those with operational actions. In the incident presented in this paper, the resonance frequency (f_{res}) of the resonance circuit was close to the operating frequency of the grid (f_{sys}) e.g. about 50 Hz and a non-linear inductance, 400 MVA power transformer, was connected to the circuit. When the circuit was disconnected, the transformer oscillated in and out of its saturation region, implying ferroresonance conditions. After few seconds, the system reached a new equilibrium point where the transformer was saturated and the system was in a sustained parallel resonance state. The possible consequences of ferroresonance and parallel resonance are high voltages that may prevent the planned switching actions or even damage the equipment in the grid [6−10]. Thus, it is important to consider the risk of ferroresonance and subsequent sustained parallel resonance occurrence when planning the operational actions.

The sustained resonance incident occurred immediately after a transmission system segment comprising of a series connected power transformer and a shunt compensated transmission line was disconnected from the grid. This topology may take place during real system restoration, for example, by relay maloperation, caused by exceptional voltages as shown in [1]. The disconnected segment had a parallel 400 kV transmission line connected to the power system at the same right-of-way supplying the resonance circuit through a capacitive coupling.

Index Terms

Ferroresonance, Power system analysis, Power system operation, Power system restoration, Sustained parallel resonance

During the early stages of system restoration, the power flow is almost zero. In the Finnish transmission system, there may be only a few generators connected to the system. Consequently, the system is very weak and there is only a little reactive power compensation capacity from the generators connected to the system. For this reason, the connected generation cannot absorb the reactive power required for the compensation of capacitive reactive power of the 400 kV transmission lines that are being energised. Therefore, in the Finnish system, the 400 kV transmission lines are almost 100% shunt compensated to avoid excessive reactive power flows and overvoltages. In this situation, a capacitive coupling, e.g. from a parallel already connected transmission line in the same right-of way, may induce significant voltage to a disconnected transmission line and provide an energy source for the possible ferroresonance [11] and subsequent sustained parallel resonance circuit. Thus, there is a need to understand how the transmission line shunt compensation level should be considered in restoration planning.

Although the descriptions of the ferroresonance mechanism [5−18] and parallel resonance mechanism [19−23] exist in the literature, there are not many papers focusing the analyses required in restoration planning to identify risk of ferroresonance and subsequent sustained parallel resonance occurrence and to prepare operational actions to avoid the sustained resonance occurrence. A problem of system restoration planning is that the exact operating conditions and circuit topologies during the restoration are not known in advance. Thus, several assumptions of the likely operating conditions during the restoration actions must be made and simulations without reference field measurements may not necessarily reflect to the conditions encountered when executing the real restoration actions. In addition, it is difficult to validate simulation models without field measurements.

This paper broadens the understanding about the operational conditions that make the system prone to ferroresonance and subsequent sustained parallel resonance when executing restoration actions. This is accomplished by studying the basic characteristics of induced voltages, which supply the resonance circuit through a capacitive coupling, and the mechanism triggering the ferroresonance and subsequent sustained parallel resonance when performing restoration actions. After that, the paper studies how the resonant frequency of the isolated segment affects the sustained resonance occurrence. In addition, the paper discusses how the resonance frequency may be changed using operational actions such as changing the amount of shunt compensation or varying the on-load tap changer position (OLTC) in case of a transformer connected shunt compensation. Since transformer connected shunt compensation is used in the Finnish system, the paper finally shows how the OLTC position variation can be used to manage the resonance frequency and even attenuate an already triggered sustained resonance event.

Documented studies presenting also field-test experiences serve as important references for system restoration planning. Based on simulation models validated using the field measurements, this paper studies the mechanism of the ferroresonance and subsequent sustained parallel resonance, analyses how the risk of sustained resonance occurrence may be managed during restoration and presents how the risk of sustained resonance occurrence should be considered in restoration planning.

1.2 Literature review

1.2.1 Sustained fundamental frequency ferroresonance during system restoration

CIGRE technical brochure 569 [5] and technical brochure 712 [24] identify that operating conditions during system restoration may make the system prone to ferroresonance. The brochure [5] states that rare grid topologies making the system prone to ferroresonance may seem unrealistic during normal system operation but they may occur during system restoration. For this reason, those topologies should be identified during system restoration [5].

Generally, studies analysing capacitive coupling causing sustained ferroresonance during power system restoration, especially using field-test measurements and validated simulation models, have received less attention in the literature. This and the above outcomes from [5] highlight that more detailed analysis focusing on system restoration is needed since the operating conditions and uncertainties affecting the phenomenon during system restoration may be significantly different from the normal system restoration.

1.2.2 Ferroresonance involving a power transformer and a disconnected transmission line during normal system operation

In [11], a ferroresonance occurred with a disconnected power transformer and a disconnected transmission line having a transmission line connected to the power system at the same right-of-way. A disconnected 1000 MVA transformer and 30.5 km long 525 kV transmission line were connected to each other but were otherwise disconnected from the power system. The ferroresonance incident occurred due to the parallel 525 kV transmission line connected to the power system, which supplied energy for the ferroresonance circuit through the capacitive coupling between the disconnected and connected lines. A similar incident has been reported by [17].

Both [11] and [17] conclude that the capacitive coupling between the parallel connected transmission line had a significant role in the ferroresonance since the capacitive coupling from the parallel system supplied energy to the resonance circuit. Furthermore, one of the conclusions in [11] was that disconnected transmission lines should be disconnected from transformers as soon as possible to prevent ferroresonance. This may not be possible during power system restoration if large transmission system segments are being switched during system energisation and the inductive shunt compensation, which is required during restoration, is connected to the system through transformers.

1.2.3 Induced voltages due to capacitive coupling near resonant conditions during normal system operation

During system restoration, the transmission line capacitance should be compensated by the inductive shunt compensation already before the transmission line is being connected to the system to avoid overvoltages. If the capacitance is almost hundred percent compensated by the inductance, the system is near parallel resonance conditions.

The studies in [19−23] show that if a disconnected transmission line is operated close to resonant conditions and have a parallel connected transmission line at the same right-of-way, dangerous overvoltages may be induced from the parallel transmission lines due to the, even small, capacitive coupling between the lines [19−23]. A common recommendation to avoid induced voltages is to avoid resonant conditions on the transmission lines [19−23]. However, this is not always possible during system restoration as explained in Section 1.1.

During restoration, already connected and energised parts of the transmission system may induce voltage to the disconnected parts through capacitive coupling and supply the resonance circuit. This may become a significant issue if several transmission lines are at the same right-of-way.

1.3 Contribution of this paper

The paper studies the mechanism of a ferroresonance and subsequent sustained parallel resonance during system restoration and how the sustained resonance can be avoided with operational actions during system restoration. In addition, this paper presents methods for analysing the risk of sustained resonance occurrence in restoration planning. The paper uses field measurements and simulations using validated EMT simulation models from a resonance incident in the Finnish 400 kV transmission system encountered during power system restoration field-tests.

In system restoration planning, a general objective is to maintain normal operational voltage and avoid excessive reactive power flows in the transmission system by using shunt compensation. However, this paper shows that this common restoration planning objective may cause, in certain circumstances, the transmission system to be operated close to parallel resonance conditions and makes the transmission system prone to ferroresonance and subsequent sustained parallel resonance. This paper shows that during restoration planning, the parallel resonance frequencies of the transmission system segments being energised should be studied and operational actions to avoid resonant conditions should be prepared. In addition to system restoration, similar topologies may also be encountered during normal system operation.

This paper also shows that during restoration the risk of ferroresonance and subsequent sustained parallel resonance occurrence may be significantly reduced by adjusting the parallel resonance frequency of the segment being energised. In addition, the paper shows that already excited sustained resonance may be attenuated by increasing the segment resonance frequency to be higher than the operating frequency of the parallel system which supplies the resonance circuit through the capacitive coupling.

The findings of the paper highlight that it is important that system operators responsible for restoration plans understand the interaction between capacitive induced voltages, parallel resonance and ferroresonance during system restoration to be able to identify and address the problem in their restoration plans. The paper also provides an approach to determine recommendations for the operation of transmission system segments during the early stages of the system restoration and practical operational actions.

1.4 Paper organisation

The paper is organised as follows. Section 2 presents the theory of parallel resonance and ferroresonance. Section 3 presents the encountered ferroresonance and subsequent sustained resonance incident and the field-measurements. Section 4 presents simulation models used in the study and the model validation results. Section 5 analyses the relation between the harmonic impedance, capacitive coupling, and steady-state induced voltages. Section 6 analyses the process leading to ferroresonance and subsequent sustained parallel resonance state during system restoration. Section 7 analyses how the sustained resonance occurrence may be managed in the restoration plans and how an already triggered sustained resonance may be attenuated. Section 8 presents the discussion and conclusions are presented in Section 9.

2. Theory

2.1 Fundamental frequency ferroresonance

Ferroresonance may be described as the electric circuit conditions where non-linear inductance, such as a ferromagnetic transformer core, is oscillating into and out of its magnetic saturation region and the oscillation involves a capacitance [5, 6, 25]. Ferroresonance has been encountered in various circuit configurations. The basic requirements are non-linear saturable inductance, capacitance and an energy source supplying the circuit losses. [6−10]

Fig. 1 shows an ideal circuit (no resistance) with a voltage source V_{src}, capacitance C (reactance X_C) and non-linear inductance L (reactance X_L). Fig. 1 also shows the current and voltage (I-V) characteristics of the voltages across the non-linear inductive reactance X_L and linear capacitive reactance X_C with different values of capacitance C. Fig. 1 shows that X_L has highly non-linear I-V characteristics, due to saturation, and X_C has linear characteristics. [6−10]

The rigorous mathematical analysis of ferroresonance is complex [6−10]. However, as shown in [6−10], fundamental frequency linear circuit analysis [6−10] may be used to study the ferroresonance characteristics of the circuit. The detailed theoretical analysis of the conditions where ferroresonance occurs in the circuit in Fig. 1, such as the studies in [6−10], are out of the scope of this paper.

Fundamental frequency linear analysis examines the characteristics of the circuit by analysing the circuit current (I) and voltage (V_{src}) satisfying Equation (1) [6−10].

$$\underline{V}_{\mathrm{src}} = \underline{I}\left(\mathrm{j}X_{\mathrm{L}} - \mathrm{j}X_{\mathrm{C}}\right) \tag{1}$$

By analysing the number and stability of the I-V operating point satisfying Equation (1) with different values of X_L and X_C, it is possible to estimate the risk of ferroresonance occurrence [6−10].

As shown in detail in [6−10], circuit in Fig. 1 may have several stable and unstable I-V operating points satisfying Equation (1). The presence of multiple stable operating points indicates the tendency for ferroresonance oscillation. [6−10] Analyses in [6−10] show that ferroresonance circuits are sensitive to the circuit parameters and initial conditions and, that the behaviour of circuits is difficult to predict. [6−10]

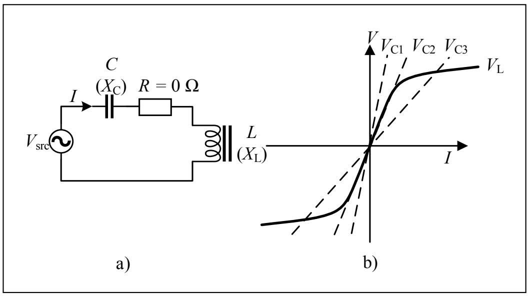


Fig. 1. (a) A circuit with voltage source V_{src}, capacitance C (reactance X_C) and non-linear inductance L (reactance X_L). The resistance $R = 0$. (b) shows the voltage-current characteristics of the circuit. The black line represents the non-linear characteristics of the voltage V_L over inductance L as a function of current I. Dashed lines represent the voltage V_C over capacitance C with different capacitance C and respective X_C values. Modified from [6] Fig. 12, [7] Fig. 7 and [8] Fig. 1.7.

2.2 Transmission line capacitive coupling near resonant conditions

A ferroresonance circuit needs an energy source, such as capacitive coupling of a parallel transmission line, to supply the losses of the circuit and sustain the resonance. [11, 17, 26]

Focusing the analysis on the capacitive coupling is relevant since the coupling may exist even when the power transfer of the transmission lines is small. Such conditions may occur for example during power system restoration. For this reason, inductive coupling is not analysed in this paper.

Fig. 2 shows two transmission lines located at the same right of way. One transmission line is connected to the power system and another is disconnected (i.e. the circuit breakers at line ends are open). Capacitance c_{ind} is the capacitive coupling between the lines, which supplies the energy for the disconnected line. In practice, the capacitive coupling is asymmetric but in Fig. 2 the coupling is represented as a symmetric capacitance to simplify the figure and analysis. Respectively, the series impedance of the transmission lines is neglected since they are insignificant compared to the transmission line capacitance and transformer and reactor inductance.

Fig. 2 also shows the shunt capacitance c_{TL} of the disconnected transmission line and shunt inductance L_{L1} representing the inductive shunt compensation. The transmission line and transformer series impedances are neglected to highlight the parallel LC characteristics of the disconnected transmission system segment. Thus, the parallel resonance frequency f_{res} of the segment can be calculated using the well-known equation:

$$f_{res} = \frac{1}{2\pi\sqrt{L_{L1}c_{TL}}} \tag{2}$$

In Fig. 2, the air core shunt reactors, having inductance L_{L1} and L_{L2}, control the 400 kV voltage and are connected to the system through the 21 kV winding of a transformer equipped with an on-line-tap-changer (OLTC). The three phases of each reactor are delta-connected and the reactors are floating (i.e. not grounded). At 21 kV voltage, the rated reactive power of each reactor is 66 Mvar.

In the topology in Fig. 2, the transformer OLTC tap position affects the transformation ratio and consequently the impedance of the transformer and tertiary reactors L_{L1} and L_{L2} as seen from the 400 kV side of the transformer. This is demonstrated in Table 7 in Section 7.2. Thus, the transformer tap position affects f_{res}.

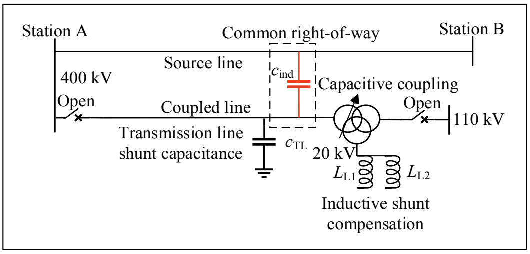
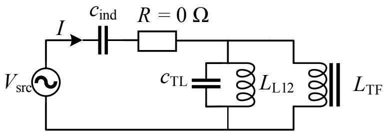


Fig. 2. Simplified circuit of the detailed circuit shown in Fig. 4. The disconnected (coupled line) and connected (source line) transmission lines in parallel. The transmission line series impedance is neglected to highlight the capacitive coupling and the system LC circuit characteristics. The transformer is equipped with OLTC at the high voltage side windings. Reactors having inductance L_{L1} and L_{L2} are air-core shunt reactors for the 400 kV system voltage control.

2.3 Circuit with both ferroresonance characteristics and parallel resonance characteristics

A circuit may have both ferroresonance and parallel resonance characteristics. This is illustrated in Fig. 3 which combines the circuits in Fig. 1 and Fig. 2.

In the circuit in Fig. 3, a ferroresonance may occur, for example, in series between the capacitance c_{ind} and transformer inductance L_{TF}. Similarly, a parallel resonance may occur, for example, between the transmission line shunt capacitance c_{TL}, shunt compensation inductance L_{L12} and transformer inductance L_{TF}.



Fix 3. A circuit with both ferroresonance and parallel resonance characteristics. The figure combines the circuits shown in Fig. 1 and Fig. 2 to illustrate the ferroresonance and parallel resonance characteristics. Capacitance c_{ind} is the capacitive coupling between the transmission lines in Fig. 2, c_{TL} is the transmission line capacitance, L_{TF} is the non-linear transformer inductance and L_{L12} represents the inductance of the shunt reactors in Fig. 2. The circuit neglects the losses to highlight the ferroresonance and parallel resonance characteristics.

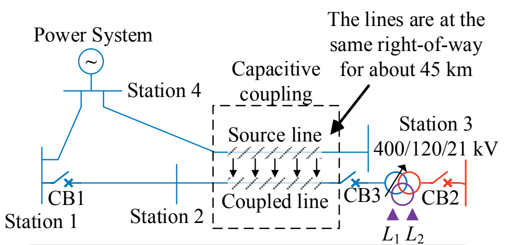
3. Sustained resonance incident

3.1 Description of the grid and switching actions

The sustained resonance incident presented in this paper occurred during power system restoration field-tests. Fig. 4 is the schematic diagram of the grid. The operating frequency of the system was 50 Hz.

The resonance occurred in the transmission system segment comprising of the transmission line Station 1 – Station 2 – Station 3 and the transformer and (Fig. 4), at Station 3. The air core reactors were connected to the 21 kV tertiary winding of the transformer and are delta-connected and floating (not grounded). At 21 kV voltage, the reactive power of each reactor is 66 Mvar. The transformer 400 kV winding grounding impedance is provided in Table 6 and the transformer 110 kV winding is not grounded. During the incident, the transformer tap position was 8 corresponding to 103.99 % transformation ratio.

In the Finnish system, the shunt reactors at a substation are designed to regionally compensate the capacitive reactive power of the transmission lines connecting to the substation. The advantage of this configuration is that it is possible to use similar shunt compensation units that can also be replaced with each other. However, for this reason, there is no specific shunt compensation level for each transmission line and the compensation level varies during different switching procedures. Also, during certain switching procedures, near resonant conditions may occur if the capacitive reactive power of the transmission lines and the inductive reactive power of the shunt compensation cancel each other.



	CB1	CB2	CB3
Before resonance	Closed	Open	Closed
During resonance	Open	Open	Closed
After resonance	Open	Open	Open

Fig. 4. The schematic diagram of the 400 kV grid where the ferroresonance and subsequent sustained parallel resonance occurred during the restoration field-tests and the respective circuit breaker (CB) statuses. The distance between Station 1 and Station 2 is about 60 km and the distance between Station 2 and Station 3 is about 100 km. L_1 and L_2 are the inductive shunt reactors connected to the tertiary winding of the transformer at Station 3. The rated voltages of the transformer windings are: 400 kV, 120 kV and 21 kV. On the right side of the open CB2, there is an energised 110 kV grid. The transformer is equipped with an OLTC at the high voltage side windings.

Table 1 summarises the detailed switching actions before, during and after the sustained resonance incident. Before the incident, circuit breakers CB1 and CB3 (Fig. 4) were closed and CB2 was open. The incident occurred immediately after the transmission system segment was disconnected by opening circuit breaker CB1 (CB2 was open and CB3 was closed).

The test arrangements described above do not necessarily represent the exact restoration procedure after a blackout for the grid shown in Fig. 4. However, the encountered and documented sustained resonance incident serves as an important reference for the system restoration planning for the following reasons:

1) During system restoration, the topologies of the transmission system segments being switched may have characteristics that are similar to the topology shown in Fig. 4.
2) There may already be connected parallel transmission lines providing energy source for the resonance circuit.
3) During system restoration, CB1 could have opened due to, for example, the unintentional action of relay protection as reported, for example, by [1].

After CB1 was opened, supervisory control and data acquisition (SCADA) measurements at the control centre did not indicate high voltages. However, after about 4 minutes, personnel at Station 3 reported suspicious noise from the transformer. The transformer was then disconnected by opening circuit breaker CB3 and the noise disappeared.

3.2 Measurements

Fig. 5 shows the voltage waveforms at Station 2 recorded by a transient fault recorder at Station 2 during the resonance incident.

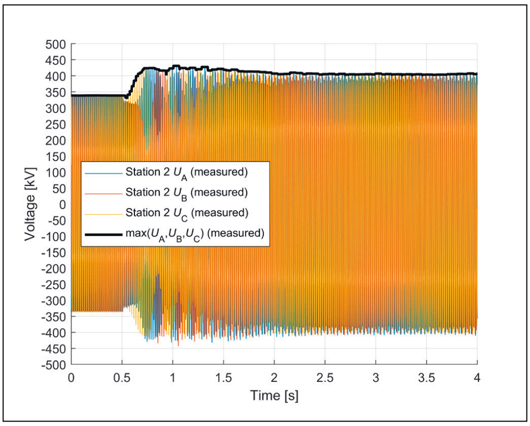


Fig. 5. Station 2 transient fault recorder measurements during the resonance incident. The resonance was triggered by opening CB1 as described in Step 2 in Table 1 and Fig. 4. The black curve shows the line-to-earth voltage peak values.

Before the incident, the line-to-earth peak values at Station 2 were about 330 kV corresponding about 404 kV line-to-line RMS voltage. After the circuit breaker CB1 (Fig. 4) was opened, the resonance excited and the line-to-earth voltages rose to about 400 kV corresponding about 490 kV line-to-line RMS voltage. This voltage level sustained about 4 minutes until the resonance circuit was broken off by opening circuit breaker CB3 (Fig. 4).

Table 1 The steps before, during and after the ferroresonance incident

Step	Description
1. Initial stage	CB1 and CB3 were closed, CB2 was open and the transformer at Station 3 and shunt reactors L_1 and L_2 were radially connected to Station 1.
2. CB1 is opened	The Transformer at Station 3, shunt reactors L_1 and L_2 and the transmission line between Station 1 and 3 (via Station 2) were disconnected by opening CB1 at Station 1.
3. Ferroresonance	Noise observations from the Transformer at Station 3.
4. CB3 is opened	The resonance circuit was disconnected by opening CB3.

Fig. 6 shows an example of the waveform and the harmonic contents of the voltage at Station 2 when the time was about 4 seconds. Fig. 6 shows that the voltage has significant 50 Hz component (fundamental frequency) but also a small 150 Hz component (the 3rd harmonic).

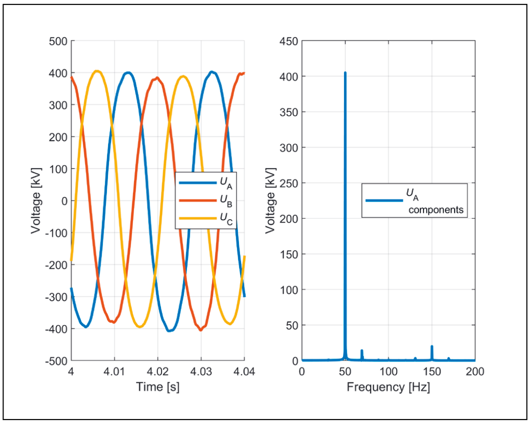


Fig. 6. A zoomed example of Station 2 voltage waveforms from Fig. 5 about 3.5 seconds after CB1 was opened and their harmonic content.

Fig. 7 shows the development of the observed 150 Hz component during the ferroresonance incident. The levels of the other harmonic components were significantly lower than the 150 Hz component. For this reason, those components are not included in the Fig. 7.

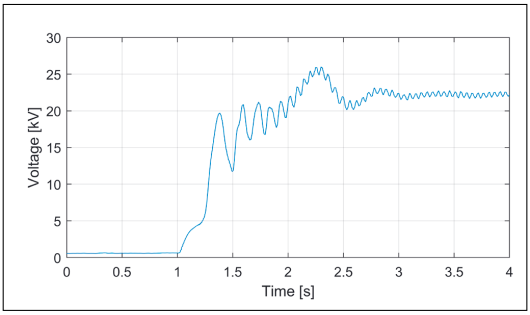


Fig. 7. The development of the 150 Hz component in the field measurements during the resonance incident.

Fig. 8 shows the waveforms of the phase currents at Station 2 (towards Station 3). Fig. 8 shows when the circuit breaker was opened, the line current started increasing and oscillating until the system reached the new equilibrium point. As shown in Fig. 8, even at the new equilibrium point, the phase currents are highly distorted.

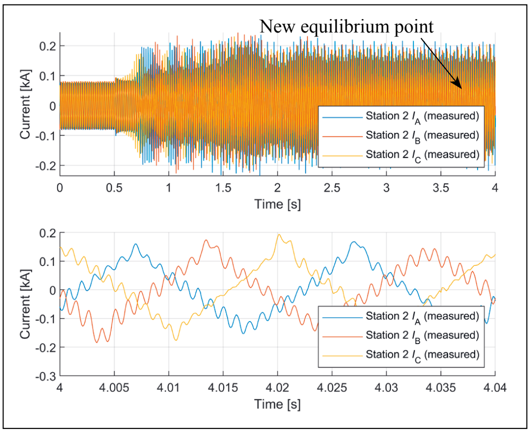


Fig. 8. Phase currents from Station 2 to Station 3 measured at Station 2 (Fig. 4) and a zoomed example of the currents when the time is about 4 seconds.

In the Finnish 400 kV system, the maximum continuous operating voltage is 420 kV (line to line RMS) which was well exceeded during the incident. Regarding temporary overvoltages, the equipment in the Finnish 400 kV system should sustain 520 kV line to neutral RMS voltage at 50 Hz frequency for 60 seconds. However, the reported incident sustained much longer. Thus, the components in the resonance circuit experienced voltage levels outside their designed operating conditions.

4. Transmission system modelling and model validation

4.1 Simulation models

The system in Fig. 4 was studied using two models: 1) the detailed validated electromagnetic transient (EMT) model and 2) the lumped EMT model. Both models were implemented in PSCAD simulation software. The detailed validated EMT model was used to study the mechanism of ferroresonance and subsequent sustained parallel resonance in the field-test grid while the lumped EMT model was used to study the basic characteristics of the induced voltages.

4.2 Detailed electromagnetic transient model

4.2.1 Model description

The detailed validated EMT model includes detailed frequency dependent transmission line models also modelling the structural design of the lines and towers, line transpositions and mutual coupling between the parallel lines. Transformer saturation characteristics are modelled using air core reactance, magnetising current and knee voltage (1.13 p.u.). The two floating delta-connected air core reactors are modelled as a passive inductance (0.02123 H for each shunt reactor). At 21 kV voltage, the rated reactive power of each reactor is 66 Mvar. The rated voltages of the transformer windings are: 400 kV, 120 kV and 21 kV. The transformer 400 kV grounding impedance is provided in Table 6 (Section 4.3). 120 kV and 21 kV windings were not grounded.

4.2.2 Model validation: induced voltage

The induced voltage due to the capacitive coupling was validated by comparing the field measurements from Station 2 (Fig. 4) and the simulation results from the detailed EMT model. The induced voltages at Station 2 were validated in two switching configurations:

1) CB1 and CB3 are open.
2) CB1 and CB2 are open and CB3 is closed.

The results in Tables 2 and 3 indicate good correlation between simulation results and field measurements.

Table 2 Voltages at disconnected Station 2 (Fig. 4) when both CB1 and CB3 are open

	$U_A\angle\theta$ [kV]	$U_B\angle\theta$ [kV]	$U_C\angle\theta$ [kV]
Measured	$4.0\angle 0^\circ$	$1.8\angle 20^\circ$	$9.0\angle 280^\circ$
Simulated	$3.3\angle 0^\circ$	$1.1\angle 30^\circ$	$8.8\angle 270^\circ$

Table 3 Voltages at Station 2 (Fig. 4) when CB1 and CB2 are open and CB3 is closed (the disconnected transformer and line are connected to each other)

	$U_A\angle\theta$ [kV]	$U_B\angle\theta$ [kV]	$U_C\angle\theta$ [kV]
Measured	$50\angle 0^\circ$	$55\angle 50^\circ$	$95\angle 200^\circ$
Simulated	$51\angle 0^\circ$	$62\angle 30^\circ$	$103\angle 195^\circ$

The model validation measurements were recorded separately from the resonance incident. During the measurement arrangements, the network topology was the same as during the ferroresonance incident. However, the switching sequence was different than during the encountered ferroresonance incident. When ferroresonance occurred, the energised transmission line and transformer were both disconnected by opening the circuit breaker. During measurements, the transformer was first disconnected from the transmission line and then the transmission line was disconnected. After that, the unenergized transmission line and transformer were connected. This eliminated the switching transients saturating the transformer and triggering the resonance.

4.2.3 Model validation: time-domain response during the sustained resonance incident

Fig. 9 shows the transient response of the simulation model when the sustained resonance is excited by opening circuit breaker CB1 (Step 2 in Table 1). The comparison of the measured waveform in Fig. 5 and the simulated waveform in Fig. 9 indicates that measured and simulated system responses are similar although simulated response produces higher transient voltages than measured.

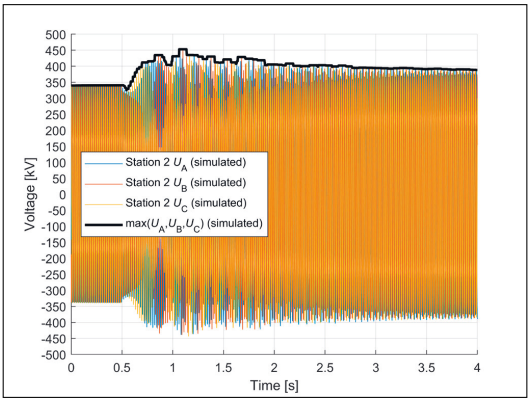


Fig. 9. Station 2 simulated voltage waveforms during the sustained resonance incident. The resonance was triggered by opening CB1 as described in Step 2 in Table 1 and Fig. 4. The black curve shows the line-to-earth peak values.

Fig. 10 shows the line-to-earth voltage peak values from measured voltages shown in Fig. 5 and simulated voltages in Fig. 9. Fig. 10 also shows that the measured and simulated responses are similar but the simulated response produces slightly lower voltages some seconds after the resonance has been excited. Further analyses are required to explain the differences between the measurements and simulation results. The analysis could focus on, for example, the impact of transformer losses and hysteresis modelling. However, these analyses are out of the scope of this paper.

Since the purpose of the study is to analyse the general impact and mechanism of the ferroresonance and subsequent sustained parallel resonance during system restoration, instead of the detailed transient responses, the results imply that the simulation model is suitable for the analysis.

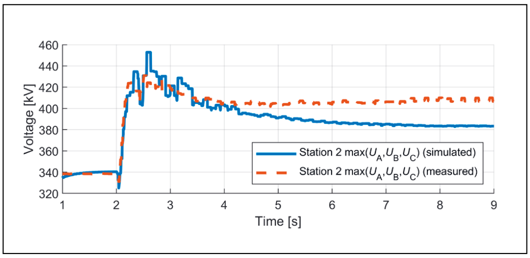


Fig. 10. The measured and simulated line-to-earth voltage peak values at Station 2 (Fig. 4) during the sustained resonance incident.

Fig. 11 shows the comparison of the 150 Hz harmonic voltage component (Station 2) obtained from the field-measurements and the component obtained using the detailed EMT simulation model. Although the EMT model produces slightly smaller 150 Hz voltage component compared to the field-measurements, the transition period of the 150 Hz component from the initial state to the new equilibrium state is similar in the field-measurements and in the EMT model. Also, it is important to note that the level of 150 Hz component is small compared to the level of the fundamental 50 Hz component in both cases. Thus, it may be concluded that the EMT model produces a 150 Hz component similar to the field-measurements. The levels of other harmonic components were significantly low compared to the 150 Hz components. For this reason, those components have not been included in the analysis.

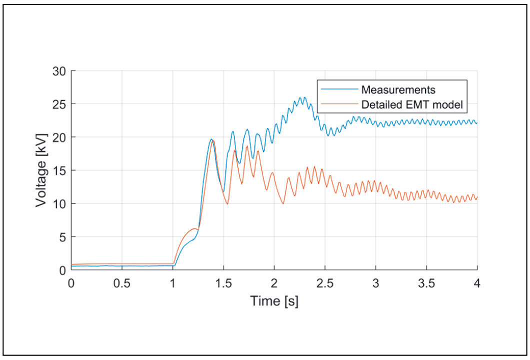


Fig. 11. The comparison of the measured and simulated (detailed EMT model) 150 Hz voltage component at Station 2.

4.3 Lumped electromagnetic transient model

Fig. 12 presents the lumped model of the system in Fig. 4 to highlight the parallel LC characteristics of the circuit. Transformer saturation characteristics are modelled using air core reactance, magnetising current and knee voltage. Compared to the detailed EMT model in Section 4.2, the benefits of the lumped model are that it is fast to run and due to lumped design compared to the detailed EMT model it is easier to study the interaction between different phenomena and components.

To simplify the model, the capacitive coupling, c_{ind}, is assumed to locate at a single point on the high voltage side of the transformer. In the detailed EMT model (Section 4.2), the capacitive coupling is distributed along the parallel transmission lines. The value of capacitance c_{ind} (10 nF) has been selected in such way that the level of the simulated induced voltages corresponds to the measurements. In practical application, the capacitive coupling is likely to be asymmetric. In this model, the symmetric coupling is used to study the principal characteristics of the system.

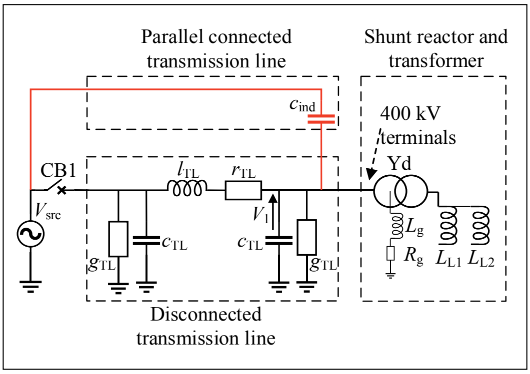


Fig. 12. The lumped representation of the system in Fig. 4 to highlight the parallel LC circuit characteristics of the system. L_{L1} and L_{L2} are the shunt reactors connected to the 21 kV winding of the transformer, c_{TL} is the transmission line shunt capacitance and c_{ind} is the capacitive coupling of the transmission lines. l_{TL} and r_{TL} are the transmission line series inductance and resistance and g_{TL} is the shunt conductance. The transmission line parameters are in Table 4, the transformer parameters are in Table 5. The transformer is grounded through the inductance L_g and resistance R_g and the parameters are in Table 6.

Table 4 Transmission line parameters for Fig. 12

c_{TL} [µF/km]	r_{TL} [Ω/km]	l_{TL} [mH/km]	g_{TL} [nS/km]
0.01296	0.01868	0.896	2.63

Table 5 Transformer parameters for Fig. 12:
P_0 is the eddy current losses, x_l the leakage resistance, S_n the transformer rating and U_1/U_2 the winding voltages.

P_0 [kW]	x_l [p.u.]	S_n [MVA]	U_1/U_2 [kV/kV]
114	0.365	400	410/21

Table 6 Grounding impedance parameters (L_g and R_g) and reactor parameters (L_{L1} and L_{L2})

L_g [H]	R_g [Ω]	L_{L1} [H]	L_{L2} [H]
0.38197	2.4	0.02123	0.02123

5. Steady-state induced voltages due to capacitive coupling

5.1 Frequency response

Induced voltages from the parallel transmission line due to capacitive coupling may provide the necessary energy source for the ferroresonance and subsequent sustained parallel resonance circuit. During system restoration, the transmission line lengths vary in the transmission system segments being energised. For this reason, it is interesting to study how the length of the transmission line being energised affects the induced voltages in the disconnected segment (the transmission line, transformer and shunt compensation in Fig. 12).

To understand the sensitivity of the induced voltages to the transmission line length, the frequency response of the disconnected segment was studied using the lumped EMT model (Section 4.3). The symmetric capacitive coupling, c_{ind} (10 nF), was assumed constant during the study.

Fig. 13 shows the magnitude of the positive sequence harmonic impedance, $|Z_+|$, at the transformer 400 kV terminals (Fig. 12) when circuit breaker CB1 is open with different values of transmission line length l. The shunt reactor L_{L1} has been selected so that the resonance frequency f_{res} of the disconnected segment when CB1 is open is the same with the operating frequency of the parallel system (50 Hz).

When the transmission system segment is in parallel resonance, the impedance of the disconnected system is the system resistance. In this case, the impedance at resonance is defined by the system losses (purely resistive). As the transmission line length increases, also the system losses increase. This can be seen in Fig. 13 as a decreased $|Z_+|$, which is purely resistive when the system is in resonance.

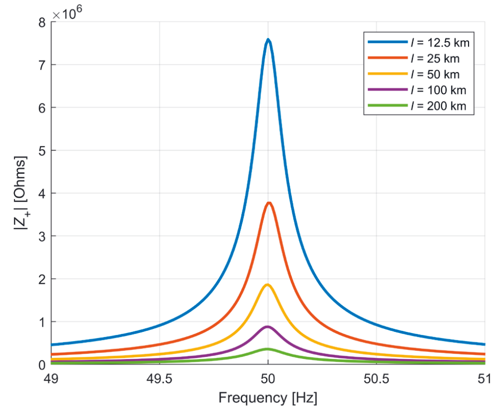


Fig. 13. The magnitude of the positive sequence harmonic impedance $|Z_+|$ at the transformer 400 kV terminals (Fig. 12) when circuit breaker CB1 is open and the transmission line length (l) is varied from 12.5 km to 200 km. The value of the shunt reactor L_{L1} has been selected so that f_{res} = 50 Hz for the segment. Capacitive coupling c_{ind} = 10 nF. The transformer is not saturated.

5.2 Steady-state induced voltages

Fig. 14 shows the induced voltage at the disconnected transmission system segment due to capacitive coupling c_{ind} as a function of the f_{res} of the disconnected segment. The analysis of the induced voltage is of interest as it indicates the ability of the capacitive coupling to supply the sustained resonance circuit. The length (l) of the disconnected transmission line was varied from 12.5 km to 200 km (Fig. 14).

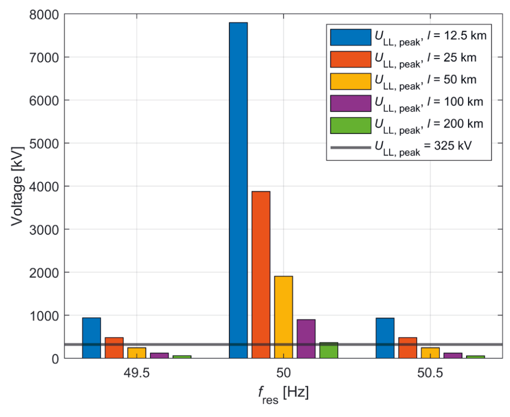


Fig. 14. Induced line-to-line voltage peak-values at transformer terminals (Fig. 12) due to the capacitive coupling between connected and disconnected systems as a function of the f_{res} of the disconnected transmission system segment and the transmission line length. Capacitive coupling is symmetric, c_{ind} = 10 nF. The black solid line is 325 kV line-to-line voltage peak value which corresponds to 400 kV RMS voltage, which correspond the typical operating voltage in the Finnish 400 kV transmission system.

Fig. 14 shows that if the resonance frequency of the disconnected transmission system segment is at the operating frequency of the parallel system (50 Hz), the capacitive coupling may induce very high voltages to the disconnected line. This is in line with the literature [5, 19−23].

Fig. 14 also shows that as the length of the disconnected transmission line increases (the losses increase), the induced voltage decreases. Increasing the losses decreases the system resistance and consequently limits the voltage rise.

Fig. 13 and Fig. 14 show that the system has a highly non-linear frequency response near resonant conditions. This means that small changes in the system parameters may have significant impact on the induced voltages. This implies that in restoration planning, it is useful to study the frequency responses and bandwidths of the critical transmission system segments being energised to understand the sensitivity of the segments to small variations in resonance frequencies. If the segment being energised is close to resonant conditions, high voltages may be induced from the already energised transmission system components due to capacitive coupling.

6. Ferroresonance and subsequent sustained parallel resonance during system restoration

6.1 Mechanism

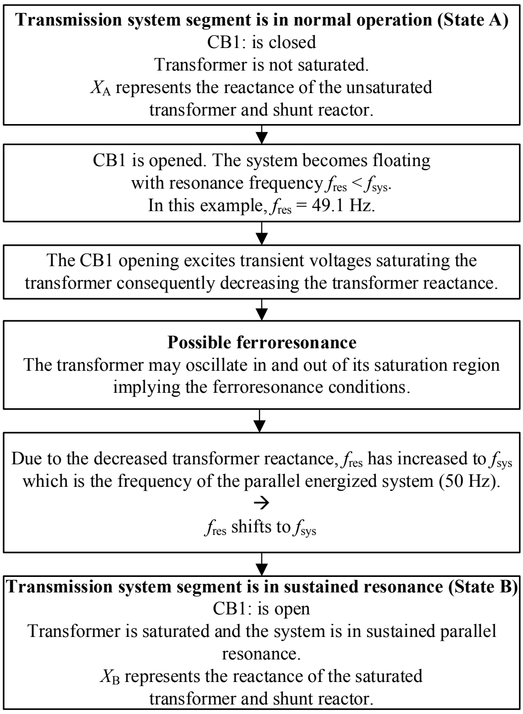
Although the ferroresonance and subsequent sustained parallel resonance incident presented in Section 3 occurred when a transmission system segment was disconnected, a similar topology may occur during system restoration when transmission system segments are being energised as described in Sections 1.1 and 3.1. If the energisation is unsuccessful, i.e. the segment is disconnected e.g. by an unintentional action of relay protection as reported by [1], the topology will be similar to the case reported by Section 3.

If the transmission line capacitance in the segment is compensated almost hundred percent by the inductive shunt compensation, the segment is near parallel resonance conditions. As described in Section 1.1, in the Finnish transmission system, these conditions may be likely during system restoration since transmission line capacitance is likely compensated using inductive shunt compensation to prevent excessive reactive power flows and voltage problems.

Switching actions during the segment energisation may cause transient overvoltages. These overvoltages may saturate the transformer (or any other non-linear inductance in the segment) and consequently change the system impedance. Equation (2) shows that when the inductance decreases (transformer saturates), f_{res} increases.

If the resonance frequency (f_{res}) of the segment being disconnected is already close to the operating frequency of the parallel system (f_{sys}), the switching transients and transformer saturation may change the system impedance and resonance frequency so that $f_{res} = f_{sys}$. In other words, the disconnected system becomes in sustained parallel resonance at the operating frequency of the parallel system. In this situation, the parallel system may supply energy to the segment as demonstrated in Section 5.

As the circuit braker CB1 is opened, the transition of the circuit from the initial steady state to the new equilibrium point is not necessarily linear. This is illustrated in Fig. 15 which shows a process where the circuit first encounters a possible ferroresonance and after that a subsequent sustained parallel resonance. In other words, the circuit may encounter both ferroresonance and sustained parallel resonance. The transition process is analysed more in detail in the next section.



Transmission system segment is in normal operation (State A)
CB1: is closed
Transformer is not saturated.
X_A represents the reactance of the unsaturated transformer and shunt reactor.

CB1 is opened. The system becomes floating with resonance frequency $f_{res} < f_{sys}$.
In this example, f_{res} = 49.1 Hz.

The CB1 opening excites transient voltages saturating the transformer consequently decreasing the transformer reactance.

Possible ferroresonance
The transformer may oscillate in and out of its saturation region implying the ferroresonance conditions.

Due to the decreased transformer reactance, f_{res} has increased to f_{sys} which is the frequency of the parallel energized system (50 Hz).
→
f_{res} shifts to f_{sys}

Transmission system segment is in sustained resonance (State B)
CB1: is open
Transformer is saturated and the system is in sustained parallel resonance.
X_B represents the reactance of the saturated transformer and shunt reactor.

Fig. 15. The process causing ferroresonance and subsequent sustained parallel resonance in the transmission system in Fig. 4. The transformer saturates and the impedance changes to a new equilibrium point through a process implying ferroresonance conditions. In the new equilibrium point, the observed system conditions are inherent to parallel resonance.

6.2 The transition to sustained parallel resonance through conditions inherent to ferroresonance

As the circuit is transitioning from the initial stage to the new equilibrium point, the transformer may oscillate in and out of its saturation region. In the literature [5, 6, 25], this behaviour is described one of the ferroresonance characteristics. As the transformer oscillation settles, after a few seconds, to the new equilibrium point, the circuit enters a sustained parallel resonance state.

The blue curve in Fig. 16 shows the development of the positive sequence component of the transformer (including the shunt reactors) positive sequence reactance, $|X_+|$, measured at the transformer 400 kV terminals (Fig. 4). The curve is obtained using the validated detailed EMT model with Tap position 8.

After circuit breaker CB1 is opened (CB2 open and CB3 closed, Fig. 4), the reactance starts to decrease due to transformer saturation by switching transients. When the reactance changes towards the new equilibrium point it oscillates until it reaches the new equilibrium point where the $f_{res} = f_{sys}$.

In the new equilibrium point, the system is in the sustained parallel resonance where the parallel system supplies the energy required to sustain the resonance (state B in Fig. 15). The red dashed line in Fig. 16 shows the calculated theoretical linear circuit value of $|Z_+|$ when $f_{res} = f_{sys}$ (50 Hz). Fig. 16 shows that the reactance value calculated from the time domain EMT results (blue curve) oscillate close to the theoretical reactance (red dashed line).

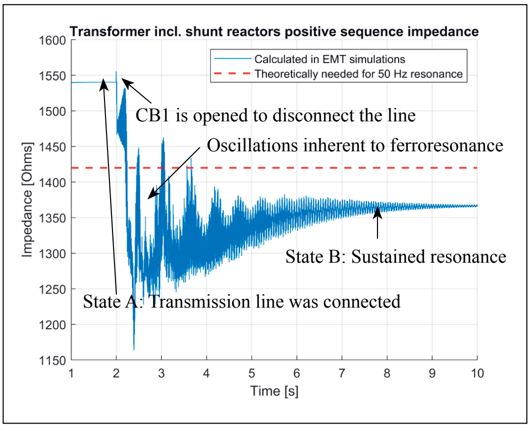


Fig. 16. The transformer and shunt reactor positive sequence reactance $|X_+|$ at transformer 400 kV terminals (Fig. 4) during the ferroresonance incident. The blue curve is the reactance calculated from the time domain EMT-simulation currents and voltages using the detailed EMT simulation model. The red dashed line is the value corresponding $f_{res} = f_{sys}$ (50 Hz) calculated using theoretical linear circuit analysis. States A and B refer to the states shown in Fig. 15.

Fig. 17 shows the relation between the 400 kV positive sequence terminal voltage and current. Fig. 17 shows that, for few seconds, the transformer impedance is oscillating significantly until it settles around the new equilibrium point.

Fig. 18 shows the transformer magnetizing current obtained from the simulations using the detailed EMT model. Fig. 18 shows the significant oscillation in the magnetizing current. Fig. 18 shows that during the transition period, the magnetizing repeatedly increases and decreases until it reaches the new equilibrium point. Fig. 18 also shows that in the beginning of the transition period, the magnetizing current repeatedly bursts indicating that the transformer is oscillating in and out of its saturation region.

The observations in Fig. 17 and Fig. 18 show that the circuit is highly influenced by the non-linear characteristics of the transformer during the transition from initial State A (Fig. 15) to sustained parallel resonance State B.

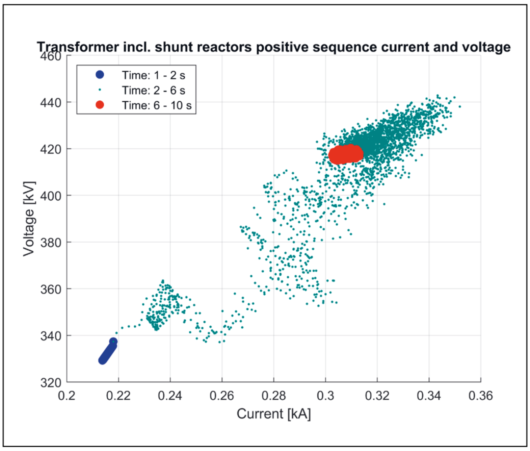


Fig. 17. The transformer positive sequence 400 kV terminal voltage and current (Fig. 4, the detailed EMT simulation model).

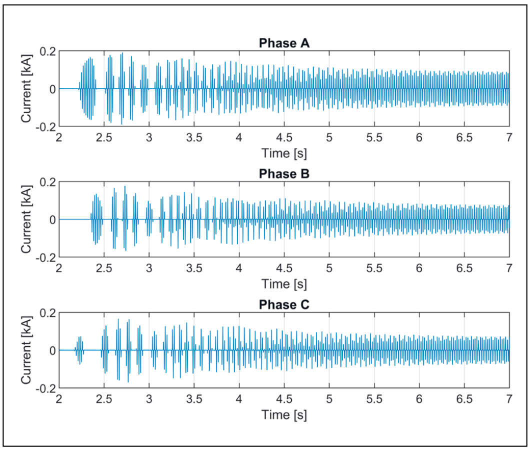


Fig. 18. The magnetizing current of the transformer (Fig. 4, detailed EMT simulation model)

To confirm the role of the non-linear inductance oscillation during the transition process, the circuit is analysed using the detailed EMT simulation model by disabling the transformer saturation function from the model. This makes the circuit linear neglecting the non-linear saturation characteristics.

Fig. 19 compares the voltage waveforms at Station 2 (Fig. 4) when the transformer saturation is enabled (non-linear circuit) and disabled (linear circuit). Fig. 19 shows when the transformer saturation does not occur, the oscillations inherent to ferroresonance and subsequent sustained parallel resonance does not occur either.

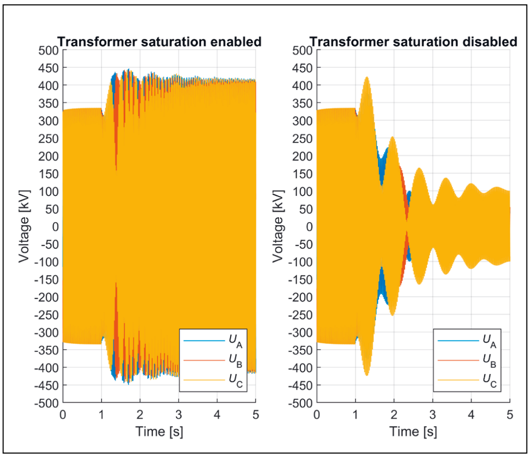


Fig. 19. Transient responses with (left) and without (right) transformer saturation. The figure represents the voltage waveforms at Station 2 (Fig. 4). The results are calculated using the detailed EMT simulation model with tap changer position 8.

7. Managing the ferroresonance and subsequent sustained parallel resonance occurrence with operational actions during system restoration

7.1 Study objective

This section studies how the changes in the segment resonance frequency f_{res} affect the ferroresonance and subsequent sustained parallel resonance occurrence and how the sustained resonance occurrence may be managed by adjusting the segment f_{res} with operational actions during system restoration. Studying the impact of f_{res} on the sustained resonance occurrence is of interest during system restoration since the switching actions during the restoration process may affect the grid topology and consequently f_{res}. Thus, the switching actions may be planned to minimise the risk of ferroresonance and sustained parallel resonance occurrence or to attenuate already triggered resonance incident.

In the field-test system (Fig. 4), the inductive shunt compensation was connected to the system through a transformer with an OLTC. Thus, it is possible to affect system resonance frequency f_{res} by changing the OLTC tap position also during real restoration actions. For this reason, the tap position was used to vary f_{res} in the simulations. However, it is important to note that system f_{res} may also be adjusted by changing the amount of inductive shunt compensation or transmission lines (capacitance) in the segment. For this reason, the results of this section may also be applied in systems without a transformer connected shunt compensation and possibility for the OLTC control.

Transformer knee voltage describes the saturation sensitivity of a transformer. Analysing the sensitivity on the knee voltage illustrates how the different types of transformers or different saturation characteristics would affect the ferroresonance and subsequent sustained parallel resonance occurrence.

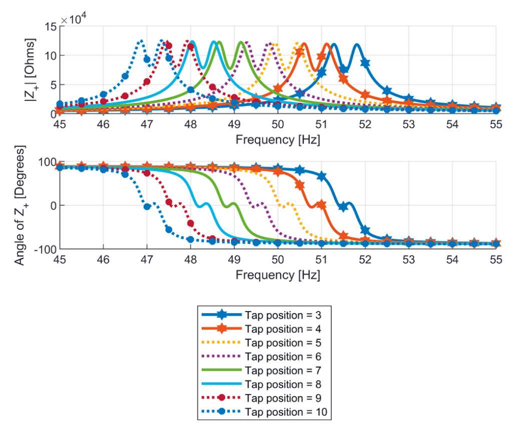


Fig. 20. The positive sequence harmonic impedance $|Z_+|$ of the system in Fig. 4 at transformer 400 kV terminals when disconnected line and transformer are connected to each other (CB1 and CB2 are open and CB3 is closed).

7.2 The impact of tap position on the harmonic impedance

To understand the sensitivity of the harmonic impedance on the OLTC tap position, a sensitivity analysis was performed using the validated detailed EMT model (Section 4.2) of the transmission system segment, where the ferroresonance incident occurred (Fig. 4)

Fig. 20 shows the positive sequence impedance at the transformer terminals with different tap positions. The f_{res} values are listed in Table 7. Table 7 also shows the transformer and shunt reactor positive sequence impedance $|Z_+|$ at the transformer 400 kV terminals with different tap positions. The impedance values were calculated

Table 7 The dual-resonance frequencies of the system in Fig. 4 and transformer (including shunt reactors) positive sequence impedance $|Z_+|$ at transformer 400 kV terminals with different tap positions.

Tap position and transformation ratio. 100 % transformation ratio corresponds to the rated 410/120/21 kV transformation ratio.	f_{res1} [Hz]	f_{res2} [Hz]	$|Z_+|$ [Ohms]
3 (97.34 %)	51.27	51.80	1350
4 (98.67 %)	50.60	51.13	1387
5 (100.00 %)	49.92	50.45	1425
6 (101.33 %)	49.27	49.80	1463
7 (102.66 %)	48.65	49.15	1501
8 (103.99 %)	48.02	48.52	1540
9 (105.32 %)	47.42	47.92	1580
10 (106.65 %)	46.85	47.33	1620

using the PSCAD simulation software. Table 7 shows that as the transformer transformation ratio changes, also $|Z_+|$ changes. Table 7 indicates that there is approximately a quadratic relationship between the transformation ratio and $|Z_+|$.

The results show that the system has two different resonance frequencies (f_{res1} and f_{res2}) for each tap position. According to the simulations, this is due to asymmetric phase shunt capacitance caused by imperfect transmission line phase conductor transposition. This is also referred to dual-resonance in the literature [27].

Fig. 20 shows that the f_{res} varies from about 46.5 Hz to 52 Hz as the tap position is changed from 3 (97.34 %) to 10 (106.65 Hz). Thus, the tap position may have significant impact on the resonance frequency.

7.3 The impact of tap position on the steady-state induced voltages

Fig. 21 shows the induced voltages in the transmission system segment in Fig. 4 as a function of tap position (Table 7) when the circuit breakers CB1 and CB3 are open and circuit breaker CB2 is closed. The study was performed using the validated detailed EMT model (Section 4.2).

Fig. 21 shows that at specific tap positions the capacitive coupling between the disconnected transmission line and the parallel connected transmission system may induce high voltages to the disconnected system. The result confirms that when the resonance frequency f_{res} of the test grid is close to the operating frequency of the parallel transmission system, the parallel system may supply high voltages to the segment establishing an energy source for the possible ferroresonance circuit.

7.4 The impact of tap position on the resonance occurrence

To understand the practical impact of the f_{res} variations on the sustained resonance occurrence in the field-test system in Fig. 4 due to changes in a tap position, a sensitivity study was performed using the detailed EMT model which was validated using the field-measurements (Section 4.2).

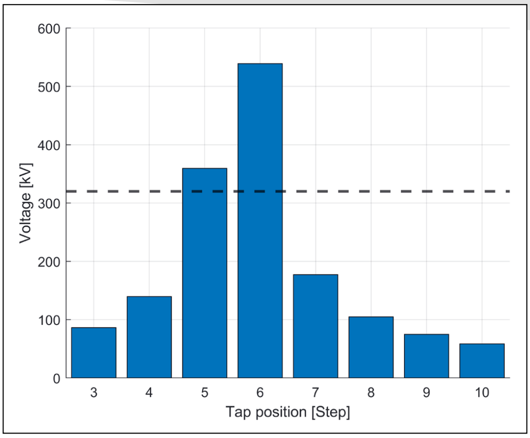


Fig. 21. Maximum line-to-earth RMS voltages at the transformer terminals in the system in Fig. 4 with different tap changer positions neglecting the transformer saturation. The corresponding resonance frequencies are in Table 7. The black dashed line is 325 kV line-to-earth voltage corresponding 400 kV line-to-line RMS voltage, which is typical operation voltage in the Finnish 400 kV system.

In the simulations, circuit breaker CB1 was opened which was also the trigger for the ferroresonance and subsequent sustained parallel resonance in the field-tests. Circuit breaker CB2 was open and CB3 was closed in the simulations. Like in the field-tests, immediately after circuit breaker CB1 is opened, the system becomes disconnected and is fed only by the capacitive coupling between the disconnected transmission system segment and the parallel connected transmission system.

The left section of Fig. 22 shows the impact of the tap changer position and consequently system resonance frequency on the sustained resonance in the system in Fig. 4. Respectively, the right section of Fig. 22 shows the level of induced voltages with each tap position shown in Fig. 21 which were calculated neglecting transformer saturation. By comparing the results of the left and right sections of Fig. 22, it is possible to compare the non-linear response (the left section, transformer saturation is enabled) and the linear response (the right section, transformer saturation is disabled) of the circuit with different tap positions. This makes it possible to identify when the transformer saturation influences the circuit response.

The results show that the tap changer position and consequently the resonance frequencies have significant impact on the ferroresonance and subsequent sustained parallel resonance occurrence.

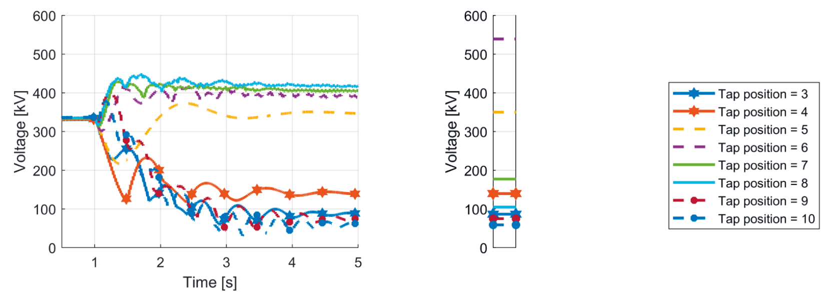


Fig. 22. The left figure: line-to-earth peak voltage values at the transformer terminals with different tap positions and resonance frequencies (Table 7) in the system in Fig. 4 when transformer saturation enabled. Sustained resonance occurs at Tap positions 7 and 8. The resonance is triggered by opening the circuit breaker CB1. Circuit breaker CB3 is closed and CB2 is open. The right figure: the induced voltages (shown in Fig. 21) with the same tap positions when the transformer saturation is neglected.

Fig. 22 shows that with Tap positions 3, 4, 5, 9 and 10 the system reaches the same new equilibrium state whether the transformer saturation is enabled or disabled. Although high voltages are observed with Tap position 5, the system is not in ferroresonance. Instead, the voltages are induced from the parallel system.

According to Fig. 22, with Tap position 6, the induced voltage is significantly higher when transformer saturation is neglected. However, this may be because transformer saturation limits the voltage rise due to linear parallel resonance when the saturation is enabled in the model.

With Tap position 7 and 8 the voltage is significantly higher in the new equilibrium point when the transformer saturation is enabled compared to the induced voltage when the transformer saturation is disabled (Fig. 22). In other words, if the circuit impedance is linear, the induced voltage is significantly lower compared to the case where circuit impedance is non-linear. With these tap positions, during the transition period, the transformer oscillates in and out of its saturation region implying ferroresonance conditions. Finally, the oscillation settles and the circuit reaches a new equilibrium point where the circuit is in sustained parallel resonance.

Table 8 summarises the above conclusions of the circuit response with different tap positions. Table 8 shows that the tap position significantly influences the circuit response during the transition period.

As the resonance frequency decreases and goes further below to the 50 Hz frequency, at some point, the sustained resonance does not anymore occur. The results also show that resonance does not occur at Tap position 4 although the resonance occurs at Tap position 8 which is further away from the 50 Hz frequency than the Tap position 4. This indicates that ferroresonance may not occur when the resonance frequency is higher than the operating frequency of the parallel system (50 Hz). This is in line with the analysis in Section 6 and [6].

Table 8 Summary of the circuit responses with different tap positions.

Tap position and transformation ratio	Response description
3 (97.34 %) 4 (98.67 %) 9 (105.32 %) 10 (106.65 %)	**Not close to parallel resonance** When transformer saturation disabled (linear circuit) or enabled (non-linear circuit), low induced voltages are observed.
5 (100.00 %)	**Near parallel resonance** When transformer saturation disabled (linear circuit) or enabled (non-linear circuit), higher induced voltages are observed compared to positions not close to the parallel resonance.
6 (101.33 %)	**Almost at parallel resonance** When transformer saturation disabled (linear circuit), induced voltage are high. When transformer saturation is enabled (non-linear circuit), transformer saturation limits the voltage rise.
7 (102.66 %) 8 (103.99 %)	**Ferroresonance and subsequent sustained parallel resonance** When the transformer saturation is disabled (linear circuit), induced voltages are low. When transformer saturation is enabled (non-linear circuit), the circuit experiences ferroresonance and subsequent sustained parallel resonance causing high voltages.

From the system restoration perspective, all operating conditions causing sustained overvoltages should be avoided since the overvoltages may damage the grid equipment. The results in Fig. 22 and Table 8 show that parallel resonance may cause overvoltages (Tap position 6) which can be seen from the linear response of the circuit. However, the results show that it is possible that although the linear system response would not indicate overvoltages (Tap positions 7 and 8), it is still possible that overvoltages are encountered due to ferroresonance and subsequent sustained parallel resonance. This risk should be identified when planning the restoration operational actions.

7.5 Attenuating an excited sustained resonance by changing the segment resonance frequency

The results in Section 7.2, 7.3 and 7.4 raise the question of the possibility to attenuate an already triggered ferroresonance and subsequent sustained parallel resonance by changing the segment f_{res}. This is studied using the detailed EMT model by changing the tap position after the sustained resonance has been triggered.

The results in Fig. 23 show that when the tap position is changed from 7 to 4 after the sustained resonance has already been excited, the resonance attenuates in a few seconds. Table 7 shows that when the tap position was 7, f_{res} was below 50 Hz (the operating frequency of the parallel system). After the tap position was changes to 4, f_{res} became over 50 Hz. Thus, by changing the resonance frequency of the segment to be higher than the operating frequency of the parallel system, the already excited sustained resonance may be attenuated.

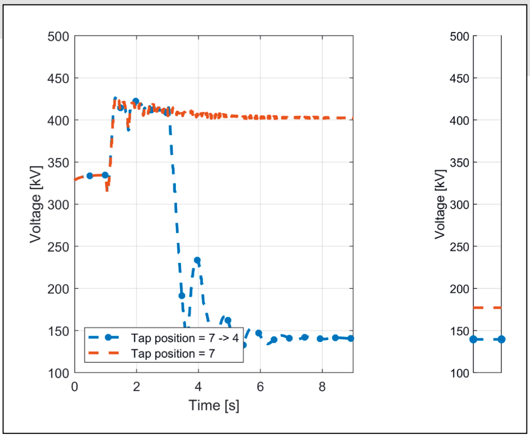


Fig. 23. The left figure: Simulated line-to-earth peak voltage values at the transformer terminals. The figure shows two simulations: 1) tap position is 7 during the whole simulation (resonance sustains) and 2) tap position is changed from 7 to 4 when the time is 3 seconds (sustained resonance attenuates after the tap position is changed). The resonance is triggered by opening the circuit breaker CB1. Circuit breaker CB3 is closed and CB2 is open. The right figure: the induced voltages (shown in Fig. 21) with the same tap positions (4 and 7) when the transformer saturation is neglected.

In order to understand how the tap position variations affect the resonance attenuation, a sensitivity study was performed. In this study, the tap position was varied from position 7 to other positions to understand when the resonance attenuates and when the resonance sustains. The results are shown in Table 9.

Table 9 shows that when the tap position change increases the resonance frequency to be higher than the operating frequency of the parallel system, the resonance attenuates. However, when the resonance frequency is initially below the operating frequency, tap positions changes decreasing the resonance frequency further below from the operating frequency do not attenuate the resonance. It may be that the

Table 9 The attenuation of already triggered resonance with different tap position variations.

Tap position variations and respective resonance frequencies (Initial position → New position) (f_{res1}, f_{res2} → f_{res1}, f_{res2})	Circuit response
7 → 3 (48.65 Hz, 49.15 Hz → 51.27 Hz, 51.80 Hz)	Resonance attenuates
7 → 4 (48.65 Hz, 49.15 Hz → 50.60 Hz, 51.13 Hz)	Resonance attenuates
7 → 5 (48.65 Hz, 49.15 Hz → 49.92 Hz, 50.45 Hz)	Resonance sustains
7 → 6 (48.65 Hz, 49.15 Hz → 49.27 Hz, 49.80 Hz)	Resonance sustains
7 → 8 (48.65 Hz, 49.15 Hz → 48.02 Hz, 48.52 Hz)	Resonance sustains
7 → 9 (48.65 Hz, 49.15 Hz → 47.42 Hz, 47.92 Hz)	Resonance sustains
7 → 10 (48.65 Hz, 49.15 Hz → 46.85 Hz, 47.33 Hz)	Resonance sustains

resonance frequency changes due to tap position changes in this study are not large enough and that a significantly larger resonance frequency change might be required to attenuate the resonance, but this requires further analysis. However, the results imply that to attenuate the sustained resonance, it is preferred to increase the resonance frequency above the operating frequency of the parallel system.

7.6 Sensitivity of the results to transformer knee voltage

To understand the sensitivity of the presented results to transformer modelling inaccuracies, a sensitivity study was performed by varying the transformer knee voltage. The results also show how different types of transformer saturation characteristics may affect the results. In this study. the transformer tap position was 8 and was not varied.

Fig. 24 shows the impact of the transformer knee voltage on the ferroresonance and subsequent sustained parallel resonance in the system in Fig. 4. Higher knee voltage means that a higher voltage is required for transformer saturation.

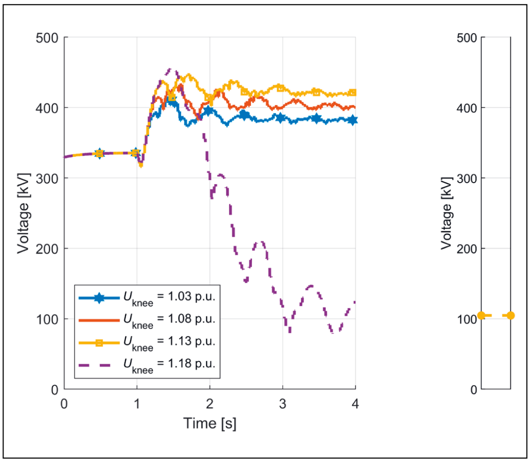


Fig. 24. The left figure: the line-to-earth peak voltage values at the transformer terminals with different transformer saturation knee voltage (U_{knee}) values in the system shown in Fig. 4 when transformer saturation is enabled. The resonance is triggered by opening the circuit breaker CB1. Circuit breaker CB3 is closed and CB2 is open. Tap position is 8 in all simulations. The right figure: induced voltage (shown in Fig. 21) when the transformer saturation is neglected (linear system) and tap position is 8.

The results in Fig. 24 show that increasing the transformer knee voltage increases the voltage during the sustained resonance. The results show that if the knee voltage is high enough, transient voltages may not saturate the transformer and ferroresonance and subsequent sustained parallel resonance may not occur. This is logical since the results in the Section 6.2 show that ferroresonance and subsequent sustained resonance requires transformer saturation to occur.

The results also show that the simulations of ferroresonance and subsequent sustained parallel resonance are highly dependent on the transformer saturation characteristics used in the study. For this reason, ferroresonance and subsequent sustained resonance occurrence should be studied using detailed data for each transformer.

8. Discussion

Since system level blackouts are rare and the experiences from restoration tests rarely reported, there are not much practical experiences in ferroresonance and subsequent sustained parallel resonance incidents during system restoration. High voltages during ferroresonance and parallel resonance may occur during restoration and damage the grid equipment. Consequently, this can delay or even prevent system restoration. Thus, it is important that the risk of ferroresonance and subsequent sustained parallel resonance occurrence and operational actions to the resonance are studied when planning system restoration actions. For this reason, all analysed and documented ferroresonance and sustained parallel resonance incidents occurred during system restoration actions serve as important references for system restoration planning and the modelling of the transmission system in restoration simulations.

Ferroresonance simulations are sensitive to modelling inaccuracies and the model validation is important. Thus, validated EMT simulation models are important. Otherwise, it may not be possible to analyse the risk of ferroresonance and subsequent sustained parallel resonance occurrence in system restoration planning. It is important that utilities responsible for the restoration actions test the restoration plans in practice and capture high quality field measurements that may be used to validate and improve the simulation models. If unexpected events are encountered during the tests, it is important that the events are thoroughly analysed and the lessons learned are implemented in the restoration plans.

This paper shows that the resonance frequencies of the transmission system segments being switched during restoration actions have a significant impact on the ferroresonance and subsequent parallel resonance occurrence. Although EMT models are required to study the resonance characteristics in detail and to provide detailed data for restoration planning, the resonance frequencies of the transmission system segments being switched may be used to estimate the risk of ferroresonance and subsequent sustained parallel resonance occurrence if EMT simulation results from similar segments are available. This is beneficial since calculating the resonance frequencies of the similar segments do not require EMT simulations. Thus, the resonance frequencies of all transmission system segments being switched should be systematically analysed as part of restoration planning and compared to the reference results from EMT simulations. In addition, the restoration planning should study in advance possible operational actions (e.g. the amount of shunt compensation) to influence the resonance frequencies of the segments being switched and prepare proper instructions in the restoration plans.

A common restoration planning objective is to avoid overvoltages during the early stages of the system restoration when the system may have only a small amount of generation with active voltage control and consequently limited reactive power resources. In the Finnish system, with only a few generators, the line shunt capacitance is usually almost entirely compensated by the inductive shunt reactance to avoid reactive power flows and overvoltages during system energisation. As this paper shows, this may make the system prone to ferroresonance and subsequent sustained parallel resonance in case of an unsuccessful energisation of a transmission system segment. Thus, system restoration planning should identify that these operational conditions increase the risk of sustained resonance occurrence.

The incident presented in the paper occurred on an isolated 400 kV transmission system segment comprising of a transformer and a shunt compensated transmission line, capacitively coupled with a parallel transmission line connected to the power system. The incident occurred immediately after the 400 kV transmission system segment was disconnected and a parallel transmission line induced voltage to the disconnected line. The occurred transient voltages saturated the transformer leading to ferroresonance and subsequent sustained parallel resonance. The capacitive coupling sustained the resonance for several minutes until operators manually disconnected the transformer from the circuit. During the resonance, excessive overvoltages were observed in the disconnected segment and the personnel at the substation heard loud noise from the transformer. If the incident had occurred during real restoration actions, the substation would have likely been unmanned. For unknown reasons, the sustained resonance was not seen by the control centre SCADA measurements. If the personnel had not been at the substation, the sustained resonance would have been unrecognized and had likely damaged grid equipment. In real restoration, unrecognized ferroresonance and subsequent sustained parallel resonance can delay or even prevent performing restoration actions. Thus, it is important that system operators have tools to identify ferroresonance and subsequent sustained parallel resonance in the control centre during system restoration and actions plans to mitigate it. Transient fault recorders or power system quality analysers are recommended for incident detection.

In this paper, the resonance frequency of the segment was changed using a transformer OLTC because in the Finnish system, shunt reactors are connected to the 400 kV system through a transformer with an OLTC. The OLTC position affects the shunt reactor impedance seen from the 400 kV system and consequently the segment resonance frequency. However, the results of this paper may also be applied in topologies where shunt compensation is directly connected to the transmission lines and affecting the resonance frequencies but detailed studies should be performed separately in each topology.

The analysis results also show that already triggered sustained resonance can be attenuated with operational actions. This implies that it might even be possible to design automatic substation control sequences which detect ferroresonance and subsequent sustained parallel resonance and automatically perform switching actions that increase the resonance frequency of the segment when sustained resonance is detected. However, these should be studied in future work.

This paper focuses on ferroresonance and subsequent sustained parallel resonance. However, the results in Table 8 show that depending on the transformer tap changer position, the circuit studied in the paper may produce different types of responses. For example, a parallel resonance may, under certain circumstances, also occur independently without preceding transformer saturation and possible ferroresonance.

Fast restoration processes are important to mitigate the adverse impacts of extended blackout duration. Therefore, unexpected phenomena like ferroresonance should be considered when planning restoration actions.

Although this paper focuses on system restoration, similar situations may also occur for example during maintenance when a segment is disconnected from the system.

9. Conclusions

This paper analyses ferroresonance and subsequent sustained parallel resonance during power system restoration. The target of the analysis is to study the mechanisms triggering and sustaining the resonance, how to prevent the sustained resonance with operational actions and how to analyse the risk of ferroresonance and subsequent sustained parallel resonance occurrence in restoration planning to ensure fast and robust system restoration in case of a blackout. Such analyses have received less attention in the literature. The study is based on field measurements from a ferroresonance and subsequent sustained parallel resonance incident in the Finnish 400 kV system and the validated simulation models.

The paper shows that if the resonance frequency of the studied disconnected segment being energised is within about 2 Hz of the operating frequency of the energised parallel system, saturating inductance, such as a power transformer, makes the system prone to ferroresonance and subsequent sustained parallel resonance. The saturation may be caused, for example, by the high voltages due to switching transients. The results also show that the simulations of ferroresonance and subsequent sustained parallel resonance are sensitive to the transformer saturation modelling and model parameters. Thus, detailed transformer saturation characteristics should be available when analysing the risk of ferroresonance and sustained parallel resonance occurrence during system restoration using EMT simulations. Also, field measurements are important for model validation.

The parallel resonance frequency of the transmission system segment being energised has a significant impact on the risk of ferroresonance and subsequent sustained parallel resonance occurrence. The paper shows that the ferroresonance and subsequent parallel resonance may not occur if the resonance frequency of the segment is higher than the operating frequency of the parallel energised system. However, if the resonance frequency is close to or lower than the operating frequency of the parallel system, ferroresonance and subsequent sustained parallel resonance may occur. It is important to note that near resonant conditions, also a pure parallel resonance, even without ferroresonance, may occur and cause high voltages. In this paper, the segment had transformer-connected shunt compensation and the resonance frequency was changed using the OLTC position. However, similar changes in the segment resonance frequency may be accomplished by, for example, controlling the level of shunt compensation in the segment. However, topology specific detailed studies are required.

The results also show that ferroresonance and subsequent sustained parallel resonance can be avoided by changing the resonance frequency of the segment with operational actions, such as changing the amount of shunt compensation. In addition, the paper shows that already excited sustained resonance may be attenuated by increasing the segment resonance frequency to be higher than the operating frequency of the parallel system. Thus, operational actions to affect segment resonance frequency should be studied in advance and instructed in the restoration plans.

The paper shows that EMT simulation models are required to study the risk of ferroresonance and subsequent sustained parallel resonance occurrence and provide detailed data for restoration planning. However, if EMT simulation results from a similar transmission system segment are available, the resonance frequencies of other similar segments may be used to estimate the ferroresonance and subsequent sustained resonance occurrence.

The paper also shows that it is important to pay attention to the detection of possible ferroresonance and sustained parallel resonance incidents during system restoration as SCADA measurements may not be able to detect the sustained resonance. Transient fault recorders or power system quality analysers may be used for incident detection. In real restoration, unrecognized ferroresonance and subsequent sustained parallel resonance can delay or even prevent performing restoration actions.

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IV

Developing practices for power system restoration: The Finnish experience on restoration field-testing and training

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Developing practices for power system restoration: The Finnish experience on restoration field-testing and training

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SUMMARY

This paper presents experiences of the Finnish transmission system operator Fingrid Oyj for developing the practices for power system restoration and field-testing and training the restoration processes. The paper focuses on the scenario where the top-down system restoration from the neighboring power systems or countries is not possible and the bottom-up restoration is the only alternative. The paper covers the restoration from intentionally disconnected islands and focuses on restoration using selected black-start units.

Bottom-up restoration from an automatically disconnected island, intentional islanding, has traditionally been a restoration option in Finland. The results in the paper show that successful islanding is unlikely due to the variations in the island imbalance caused by the regional consumption and the market driven generation. For this reason, the Finnish transmission system operator (TSO) cannot currently rely on the intentional islanding and the restoration using the selected black-start units has been adopted as the main bottom-up restoration strategy.

The challenge with the black-start and system energization step by step is that it may possibly result in a slow restoration process. The paper presents experiences on enhancing the process by increasing the level of automation, training operational personnel and improving the control center tools. Simplifying the restoration processes, increasing the level of automation and enhancing the measurement systems available for the control center has significantly improved the execution of the restoration plans and enabled the analysis and modeling of the rare complex phenomena possibly encountered during the system restoration. The paper shows that conventional SCADA measurements may not be enough for monitoring the phenomena during power system restoration and PMUs and transient fault recorders are highly valuable when performing restoration field-testing but also during the actual restoration actions.

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The paper shows that restoration field-testing and operator training to manage the exceptional operational conditions during restoration significantly improve the execution of restoration plans. The first tests and exercises may be slow since time may be needed to correct the possible setting errors in equipment parameters, and analyze unexpected events encountered during the process. In the paper, the first successful black-start test took almost 12 hours to complete while the second test took only 20 minutes. The first test revealed problems, which were difficult to detect in advance using simulations. After the problems were corrected and the restoration process revised, the second test was a straightforward execution of the restoration plan. In addition, the experience from the first test enabled the better training of operational personnel for the process.

KEYWORDS: Intentional islanding, Operator training, Power system restoration, Power system operation

1 ASPECTS ON THE SYSTEM RESTORATION IN THE FINNISH SYSTEM

In the bottom-up restoration, the system energization starts from the selected black-start units or intentionally disconnected islands. After that, the transmission system components, load and other generation are connected to the island. Under these circumstances, the islanded system is typically very weak (low short circuit current levels) when the long 400 kV transmission lines and power transformers are being energized. These conditions may make the system prone to poorly damped switching transients due to harmonic resonance. [1-3] In order to avoid the excessive switching transients, the short circuit levels of the system need to be increased by connecting other generating units to the system. This may significantly slow down the restoration process.

In the Finnish system, large hydro power plants are located mostly in northern Finland and the load centers are in southern Finland. The distances between the hydro generation areas, typically the most suitable for island operation, and the load centers may in some cases be several hundreds of kilometers. For this reason, the generation areas and load centers need to be connected using long 400 kV transmission system segments. In order to establish fast and robust bottom-up restoration strategies, Fingrid launched a project to revise its strategies and optimize the practices. Since the Finnish system is part of the European Union, the European network codes [4] regulate the system restoration practices.

This paper is organized as follows. Section 2 presents the background for focusing on the black-start units-based strategy instead of the intentional islanding as their main restoration strategy. Section 3 presents the enhancements implemented in the bottom-up restoration processes. Section 4 presents the experiences from the field-testing and training of the restoration processes. Section 5 presents examples of transient phenomena encountered during restoration demonstrating the need for advanced measurement systems. Section 6 presents discussion and Section 7 presents the conclusions of the paper.

2 FEASIBILITY OF INTENTIONAL ISLANDING

In intentional islanding, the selected areas in the power system are automatically disconnected from the system before the system is going to a blackout. Protection systems monitor the state of the power system and disconnect the areas when the predefined criteria are fulfilled. The islanded systems could then be used for system restoration. [5]

Intentional islanding has traditionally been considered as one restoration strategy in the Finnish system. The idea has been that the amount of generation and load in the islanded system would enable the fast restoration of the bulk transmission system connecting the islanded systems with the critical load areas. During the period of horizontally integrated, large energy companies in the late 1980’s, regional tests were performed to validate the performance of the main areas dedicated to intentional islanding.

To ensure robust intentional islanding, certain fundamental preconditions should be fulfilled. First, the frequency control resources in the islanded area should be capable of regulating the active power imbalance when the island is being formed. Secondly, the imbalance between the rest of the power system and the area to be islanded should be such, that the frequency variation right after the islanding remains within tolerable limits. In practice, the frequency variations due to the islanding of an area which is either importing or exporting power to the rest of the power system is dependent on several factors such as the island inertia and the type and control performance of the frequency control resources.

One of the key concerns regarding the feasibility of intentional islanding was related to the fact, that the electricity market drives the generation in the Finnish system. Thus, the imbalance of the areas may vary significantly. A pre-feasibility study was performed to understand if the fundamental preconditions for intentional islanding can be fulfilled considering the present structure and operation of the Finnish transmission system. For this study around 20 possible areas for intentional islanding were identified and profiled. To assess in straightforward manner the general feasibility of each area for intentional islanding, a simple power balance screening criterion was established as an indicator if a certain area can fulfil the fundamental pre-conditions for successful islanding. Area imbalances and inertia levels were compared to pre-calculated islanding criteria [6] to get an indication of the feasibility of each area for intentional islanding. Figure 1 shows how 13 potential areas in the Finnish power system fulfill the power balance screening criterion for intentional islanding. The analysis is based on 365 days of SCADA measurements.

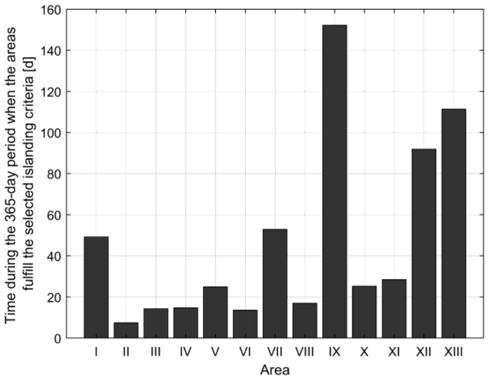

FIGURE 1: TIME IN DAYS DURING THE 365-DAY PERIOD WHEN THE AREAS I–XIII IN THE FINNISH POWER SYSTEM FULFIL THE AREA IMBALANCE AND INERTIA CRITERIA FOR SUCCESSFUL ISLANDING.

Figure 1 shows that successful intentional islanding is unlikely without redispatching actions to limit the imbalance. Even in the most promising area, the criteria were fulfilled for less than 50% of the time, and for most of the areas the same period was less than 20% of the time. This is due to the electricity market which causes significant variations in generation, and consequently to area imbalance and inertia.

Even though successful islanding could be possible, in practice the management of the islands and the maintenance of the islanding protection system becomes likely challenging. For the most promising areas further feasibility assessment concerning the type of the generation, the type of local load and overall complexity of the island topology were analyzed. In most of the cases the factors were proven to further complicate the possible islanding concept. Also, in certain areas e.g. the foreseen changes in the type of generation toward more intermittent generation or shut down of the existing synchronous machine based generation strongly indicated that establishing a new intentional islanding scheme might not be a feasible solution for a very long period of time. For this reason, the Finnish TSO cannot, at present, consider the intentional islanding as a feasible restoration strategy.

3 ENHANCING THE BLACK-START AND BOTTOM-UP RESTORATION PROCESSES

3.1 Background

Re-assessment of the bottom-up restoration strategies was launched around 2010 when few unintentional regional islanding incidents indicated that the recent topology changes and the changes in the system operational practices may have significant impact on the feasibility of the traditional system restoration practices. The feasibility studies and tests clearly indicated that the traditional restoration approaches need to be revised and critically evaluated based on the recent and projected changes in generation, consumption and system operation. On one of the key lessons learned was, that the impact of phenomena related to system technical performance can be significant on the restoration process that applies the most feasible present black-start resources and restoration paths.

3.2 Implementation of a new transmission system energization strategy

Due to the risk of harmonic resonance and consequently high and poorly damped switching transients during transmission system energization, the Finnish TSO has implemented a new transmission system energization strategy, controlled grid voltage build-up [7]. The strategy enables the fast and robust energization of the selected 400 kV transmission system segments connecting the black-start units and the critical load areas [7].

3.3 Simplifying the black-start and system energization processes

The restoration actions may become very slow if different distribution system operators and generating companies participate in the black-start and the initial system restoration. The challenge is that the number of people and organizations required for the initial restoration stages is highly dependent on the grid ownership and topology.

In order to reduce the number of people and organization participating the black-start and the initial system restoration, the Finnish restoration strategy now prefers restoration paths where the critical parts of the transmission system between the black-start unit and the critical load area may be established solely by the TSO.

3.4 Enhancing the regular field-testing and operator training practices

Whereas restoration related field tests were performed regularly until the late 1980s, it appears that in the 1990s and early 2000, the regular testing of the concepts was not proven to add significant value. Along with that trend it is obvious that the routine with the restoration related issues and the related practical insight has slowly deteriorated. Since the blackouts affecting the complete power system are rare, TSOs seldom need to execute the restoration plans. However, during the system restoration the system may experience rare phenomena seldom encountered during normal operation.

Although modern power system simulators and dispatcher training systems enable the simulation of restoration actions, these systems rely on power system modeling. Since the transient phenomena and the possible equipment malfunction during the restoration are not modeled in the simulators, they are not able to fully validate the restoration plans.

For the above reasons, in the 2010s, the Finnish TSO has adopted the regular field-testing of the restoration plans to the extent possible without significantly interfering with the normal system operation. The tests are also used for the training of operational personnel.

3.5 Increasing the level of automation in the black-start and switching processes

The start of a black-start unit may require several control actions on the unit. Performing these control actions manually may require significant amount of time and slow down the restoration. This is especially the case if the unit start-up requires communication between the TSO control center and the black-start unit operational personnel. For this reason, the following improvements have been implemented in the Finnish restoration process:

- The selected black-start units have been equipped with the SCADA remote-control capability from the TSO control center.

- Black-start unit start-up sequences (both power plant automation and TSO SCADA) have been revised in order increase the level of automation in the process.
- Black-start units, which may be started unmanned from TSO's SCADA, are preferred.

Establishing the transmission system between the black-start unit and the critical load area being restored may require an excessive switching process and several control actions. Pre-programmed SCADA sequence controls have traditionally been used to automate the switching actions. However, the pre-programmed sequences are fixed and if the restoration path needs to be adjusted, it is likely that the pre-programmed sequence will not work. In order to enhance the flexibility in the switching process, SCADA multi-point control (described below) has been adopted in the restoration process:

1. The implementation of SCADA displays which enable the selection of the switching devices such as breaker along the restoration path.
2. Using the displays, the control center operator can select and operate the required switching devices with a single SCADA control action.

3.6 Enhanced measurement systems in the TSO control center

Traditional SCADA-measurements are not necessarily able to capture the transient phenomena seldom encountered during normal system operation. However, these phenomena may be encountered during system restoration. In order to improve the ability to detect dynamic and transient phenomena by the TSO control center, the Finnish TSO utilizes PMU measurements in the control center. In addition, data from transient fault recorders (TFR) is used to further capture and analyze these phenomena.

4 EXPERIENCES FROM FIELD-TESTING THE RESTORATION PROCESSES

4.1 Restoration field-tests in 2017

The field-test with the enhanced restoration processes was performed in 2017 in the Finnish 400 kV transmission system. The target of the test was to start the black-start unit using the SCADA remote control and energize the transmission system shown in Figure 2. Figure 3 shows the timeline of the test day and Table I provides the description of the main events.

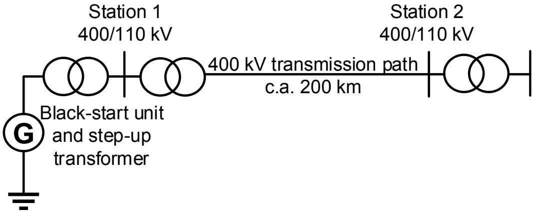

FIGURE 2: A SIMPLIFIED SCHEMATIC DIAGRAM OF THE TEST GRID.

Figure 3 and Table I show that it took about 12 hours to complete the successful black-start, transmission system energization and island synchronization. Several unexpected problems were encountered delaying the execution of the restoration plan. The issues were finally solved during the long test day enabling the successful execution of the restoration plan.

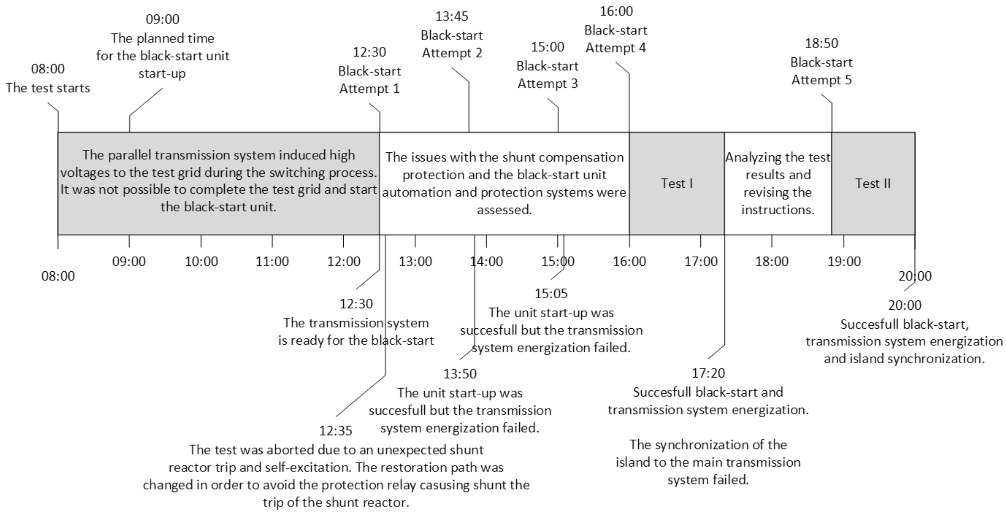

Figure 3: The timeline of the restoration tests in 2017. The description of the events is at Table I.

Table I: The description of the events in the timeline in Figure 3.

Time	Description
08:00–12:30	The test grid was disconnected from the main transmission system operating in parallel with the test grid. High and asymmetrical voltages induced to the test grid and the black-start unit automation system prevented the start-up since there was voltage in the grid. The high voltages were caused by the parallel resonance between the inductive shunt compensation and the transmission line capacitance in the 400 kV test grid. Increasing shunt compensation in the test grid changed the parallel resonance frequency of the grid and the test grid voltage went to almost zero enabling the black-start unit start-up. Since the phenomenon was not foreseen in advance, it was time-consuming to solve the issue during the field-test, which caused significant delay to the restoration process
12:00–12:35	The black-start unit start-up was successful. However, a shunt reactor in the test grid tripped and the black-start unit (a synchronous generator) became connected to highly capacitive load and started self-exciting. The self-excitation caused rapid uncontrolled voltage-rise and the test was aborted. This event is described more in detail in [8]. The trip was due to the compensated unbalance protection relay. This relay type uses a fixed current compensation calibrated at the rated voltage and current in order to compensate the natural unbalance of the shunt reactor. During the test, the voltage was exceptionally low, and the absolute current unbalance was small, but the fixed compensation setting caused the relay to unintentionally trip the reactor. [8]
13:45–16:00	Two unsuccessful tests: the black-start was successful, but the system energization failed due to issues in the black-start unit automation and protection systems.
16:00–17:20	The first successful black-start and transmission system energization. At 17:20, the planned synchronization of the island to the main transmission system failed. This was due to the unexpected behavior of the black-start unit turbine governor which caused the generator to synchronize at reverse power causing protection systems to trip the unit.
18:50–20:00	Successful black-start, transmission system energization and island synchronization to the main transmission system took all together about 60 minutes. Synchronization took about 10 minutes.

4.2 *Actions taken after the tests in 2017*

Based on the results from the 2017 tests, it was obvious that the restoration process was too slow and needed to be enhanced. Thus, the following improvements were implemented:

1. The parallel resonance between the inductive shunt compensation and the transmission line capacitances may be avoided by connecting additional shunt reactors to the system when establishing the transmission system.
2. The protection settings of all shunt reactors were revised in order to ensure that the reactors do not trip even in case of exceptionally low system voltages.
3. Black-start unit automation sequences were revised and simplified.
4. The island synchronization instructions were revised.

4.3 *Restoration field-tests in 2018*

Figure 4 shows the timeline of the restoration field-tests after the implementation of the improvements in Section 4.2. The test grid was the same used in the 2017 tests (Figure 2).

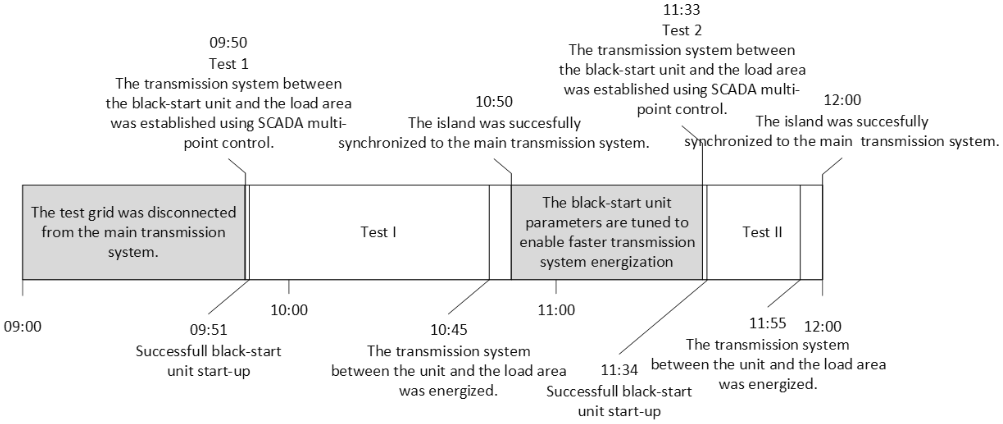

FIGURE 4: THE TIMELINE OF THE RESTORATION TESTS IN 2018.

The timeline (Figure 4) shows that the restoration process has significantly improved from the 2017 tests. Two successful tests were performed in three hours. Both tests comprised:

1. Establishing the transmission system between the black-start unit and the critical load area using the SCADA multi-point control.
2. Unmanned remote black-start unit start-up from the TSO control center.
3. The energization of the transmission system and the island synchronization.

The first test started at 09:50 and completed in 10:50 (Figure 4) lasting in total 60 minutes. After that, the generator parameters were tuned to enable even faster system energization. The second test started at 11:33 and completed at 12:00 lasting in total 27 minutes.

5 EXAMPLES OF PHENOMENA ENCOUNTERED DURING FIELD-TESTING

5.1 *Generator self-excitation*

Figure 5 shows a voltage rise due to generator self-excitation under capacitive load. This event is analyzed more in detail in [8]. Figure 5 shows that SCADA measurements are not able to capture the system response during self-excitation and seem to extrapolate the response causing significant deviation between the PMU and SCADA measurements. The analysis of the event would be impossible using only SCADA measurements.

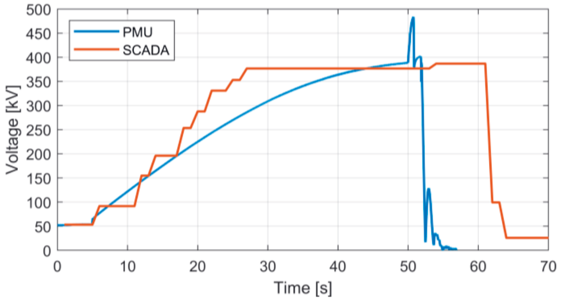

FIGURE 5: THE VOLTAGE AT A 400 KV SUBSTATION DURING THE GENERATOR SELF-EXCITATION. THE EVENT IS MEASURED USING A PMU AND CONVENTIONAL SCADA MEASUREMENTS.

5.2 Ferroresonance between a power transformer and a transmission line

Ferroresonance incidents involving unenergized transformers connected to a long unenergized transmission line having a parallel energized transmission line have been reported [9]. Similar switching operations may take place during system restoration.

Figure 6 shows a diagram of a 400 kV transmission line which was unenergized by opening the circuit breaker CB1. When the breaker was opened, a ferroresonance circuit between the transmission line capacitance, transformer and shunt reactor was formed. The energy to the circuit was induced from the parallel transmission line. Figure 7 shows the transient fault recordings (TFR) at Station B and SCADA measurements at Station B and C.

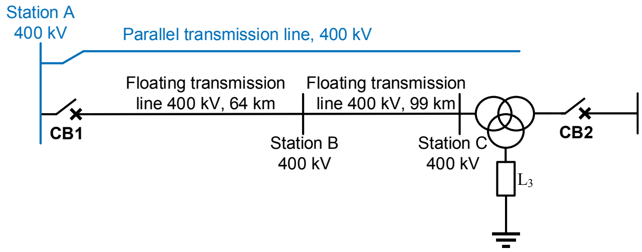

FIGURE 6: THE DIAGRAM OF THE GRID DURING THE FERRORESONANCE. CIRCUIT BREAKER CB2 WAS OPEN AND SHUNT REACTOR L_3 WAS CONNECTED. THE RESONANCE OCCURRED WHEN CIRCUIT BREAKER CB1 WAS OPENED.

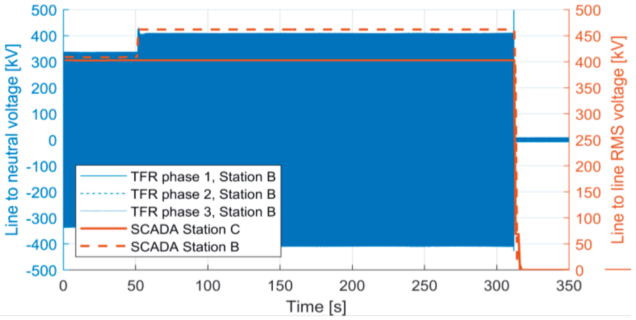

FIGURE 7: THE VOLTAGE MEASUREMENTS DURING THE FERRORESONANCE IN FIGURE 6.

The line to neutral peak voltages at Station B were about 400 kV (corresponding to about 490 kV line to line RMS voltage). SCADA measurements at Station B show an increase in the voltage but SCADA measurements at Station C do not indicate any change in the voltage. Since Stations B and C were connected to the same floating transmission line, the voltage at the stations should be about the same. The inconsistent measurements may cause confusion in the control center and make it challenging to detect a ferroresonance event.

6 DISCUSSION

The field-tests presented in the paper revealed unexpected behavior with the shunt reactor protection and black-start unit automation. In case of a real blackout, these problems would have caused significant delays to the restoration process. Since the system operation conditions during restoration deviate from the normal operation, it is difficult to detect all the possible automation and protection problems in advance using only simulations.

Regular restoration field-testing enables the detection and correction of the unexpected problems in the transmission system equipment and the restoration plan. The results show that the first restoration field-tests took 12 hours to complete but provided results enabling the correction of the issues and further revise the restoration plan. After correcting these issues and revising the restoration plan, the successful black-start and transmission system energization was performed in 27 minutes. Field-testing is also important for training. The operational personnel participated in solving the issues during the tests in 2017. This enabled gathering the comments to the restoration plan making the plan easier to execute.

The paper shows that the conventional SCADA measurements are not sufficient on the critical substation and generating stations during restoration. PMU measurements may significantly improve the observability of the system and enable capturing the rare phenomena. In addition, the possibility of transient phenomena, such as ferroresonance, highlight the need for transient fault recorders. The high-quality measurements also enable the validation and improvement of the simulation models used for the restoration planning.

7 CONCLUSIONS

This paper presents the experiences of the Finnish TSO in developing practices for power system restoration. The paper covers the restoration from intentionally disconnected islands and focuses on the bottom-up restoration of critical loads using selected black-start units in situations where the restoration from the neighboring systems is not possible.

The paper shows that intentional islanding is not currently feasible in Finland due to the imbalance varations of the possible islanded areas. For this reason, the restoration using selected black-start units has been selected as the main bottom-up restoration strategy.

The paper shows that increasing automation, enabling the remote black-start unit start-up capability from the TSO control center and performing the regular operator training and the restoration field-testing have together significantly improved the restoration processes.

The paper also demonstrates that TSOs should utilize PMUs and transient fault recorders at the critical substations, which are energized in the early stages of the system restoration.

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PUBLICATION
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Experiences of analysing seasonal oscillatory properties of the Nordic power system using large data sets

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Experiences of analysing seasonal oscillatory properties of the Nordic power system using large data sets

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SUMMARY

This paper presents analyses performed by the Finnish transmission system operator (TSO) on the occurrence, long-term patterns, and seasonal variations of the dominant electromechanical oscillation modes in the Nordic power system during 2015 and 2016. The paper also describes the developed process used to obtain the seasonal variations, which uses both spectral analysis methods and statistical methods.

With the developed measurement system and analysis process, the most dominant oscillation modes (0.5 Hz and 0.3 Hz) are extracted from the PMU data using modal identification methods and the bandwidths that represent those modes. Then the paper analyses and visualizes the seasonal variations with spectrograms and statistical methods of the selected oscillation bandwidths as a function of week of the year and operational hour. A long data set of ambient PMU measurements is used in the analysis to get an overview of the observed oscillations modes and their characteristics. The correlation of the oscillation events with generation levels, power transfers and system inertia are also analysed.

The results show that the analysed oscillations bandwidths have very different seasonal characteristics. The results also show that the characteristics vary between different years, which highlights the need for performing long-term analyses when applying spectral analysis methods. The analysis show that spectral analysis using large data sets from different years can provide transmission system operators totally new information of the variations in the modal characteristics of the transmission system. Also, the analysis may provide new information from the power system which helps transmission system operators to maintain good operational security.

KEYWORDS

Electromechanical oscillation - Modal identification – Statistical analysis - Phasor measurement unit - Spectral analysis – Seasonal variations.

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1 INTRODUCTION

The Nordic power system consists of the systems in Finland, Sweden, Norway, and eastern Denmark. The transmission distances can be as long as 2000 km and therefore stability rather than thermal limits defines the secure transmission capacity in many corridors. In a similar way as in many other systems with long transmission distances, the system has well-known electromechanical oscillatory modes, reported e.g. in [1]–[3]. One such mode is the 0.3 Hz mode, where the generators in southern Finland oscillate against the generators in southern parts of Sweden and Norway. This mode limits the transmission capacity via ac-lines when transmitting power from Finland to Sweden. Another mode is the 0.5 Hz mode, where the generators in southern Finland and southern Norway oscillate against the generators in southern Sweden. According to [4], this mode has been best observable in southern Norway. In addition, monitoring of the oscillations in the Nordic power system using Wide-Area Measurements Systems (WAMS) have been reported in several papers such as [5] and [6].

Damping of 0.3 Hz oscillation is typically of concern when power is being exported from Finland to Sweden via AC lines. General assumption has been that there should not be long term oscillation events at any frequency when power is imported from Sweden to Finland. Recently, the Finnish transmission system operator Fingrid has observed occasional poorly damped oscillations at 0.5 Hz also when importing power from Sweden. So far, the 0.5 Hz mode has been less studied than the 0.3 Hz mode. Thus, the observations raised an interest to study the mode and its occurrence and try to find out how the power system state (such as load, generator connection, grid topology) may influence the mode and if some regular seasonal patterns occur. As the frequency of an oscillation mode vary, the analysis in this paper are performed using frequency bands representing the analysed oscillation frequencies. Analysing long-term trends rather than single events can give a better understanding of the causes behind the oscillations and also possible trends that may trigger the oscillations. Here the concept long term means a period of some years. If such trends occurred, it is beneficial to know them before the system faces problems.

The paper is organised as follows. Section 2 describes the requirements for PMU data and Section 3 describes how the data are processed into oscillation amplitude results. After that Section 4 presents the results from the study and Section 5 presents the discussion about the results. Finally conclusions are presented in Section 6.

2 DATA REQUIREMENTS

The oscillatory characteristics of the AC interconnection between Finland and Sweden were analysed using the PMU measurement data from years 2015 and 2016. As PMU measurements are satellite synchronized, they make it possible to analyse power system measurements from different locations using different kinds of signal processing methods. On the other hand, PMUs also generate much more measurement data compared with conventional SCADA measurements. For example, PMUs installed on high voltage transmission system in Finland provide data with the 20 ms sampling rate.

Analysing long-term variations in power system requires large data sets. The key requirements for the data are sufficient sampling rates so that signal processing methods can be applied to the data and good availability of the data so that there are not too much time periods that are missing the measurements completely. It is also important that historic data is available from sufficient long time periods. In other words, data archives should be large enough to store full resolution PMU data for the analysis. When analysis is performed over long time periods, calculations needs to be carried out in suitable segments. Thus, data shall also be easily available via programmable application program interfaces so that analysis process can be automated.

3 FROM MEASUREMENT DATA TO OSCILLATION CHARACTERISTICS

In this study, the spectrograms [7] and two measurement-based modal identification methods are used

for estimating frequencies of the electromechanical modes. The methods are the wavelet method [8], and the multivariate autoregressive model (MAR) [9]. The methods are selected because they have been developed and applied in analysing the oscillations in the Nordic power system earlier.
The process for analysing seasonal variations in oscillatory characteristics is shown in Figure 1. First the PMU data is extracted from the WAMS data archives and linear trends from the data are removed. The filtered data is then analysed using spectrograms and modal identification methods in order to find the dominant oscillation frequency bandwidths from the data in order to understand which oscillation modes have the highest amplitudes during the analysed time period. In other words, if there are simultaneous multiple oscillation modes at the system, only the frequency bandwidth representing mode with the highest amplitude is considered to be present. This accuracy is considered sufficient as the objective is to identify when the oscillation level are higher than they usually are.

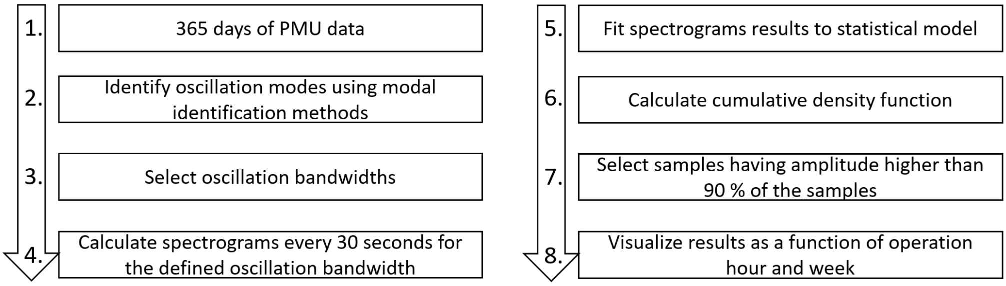

Figure 1. Process for extracting and visualizing the oscillation events from one year of raw PMU data.

After the dominant oscillation frequencies have been identified, 15-minute spectrograms are calculated every 30 seconds for selected bandwidths. For 365 days of data, the step generates about 1 million spectrograms for each bandwidth. As the purpose is to understand the general variations in oscillation characteristics during different seasons over time, spectrograms results can be used to analyse both development of oscillation events and also to calculate oscillation levels and frequencies for further analysis.

The spectrograms are analysed in order to obtain trends and variations in oscillation levels during different seasons. First the spectrograms are analysed to identify oscillation levels and frequencies. After that the oscillation frequency and amplitude variations are fitted to suitable statistical model which is then used to calculate probability distribution and density functions which can be used to identify oscillation levels that exceed selected thresholds. These events are then visualized in order to understand when the oscillation events exceeding the selected thresholds occur and analyse how oscillation periods correlate with other power system parameters such as generator mix, load level and power transfer conditions.

4 RESULTS

4.1 PRELIMINARY ANALYSIS FOR IDENTIFYING OSCILLATION MODES AND AMPLITUDES

Figure 2 summarizes the detected dominant oscillation modes during 2015.

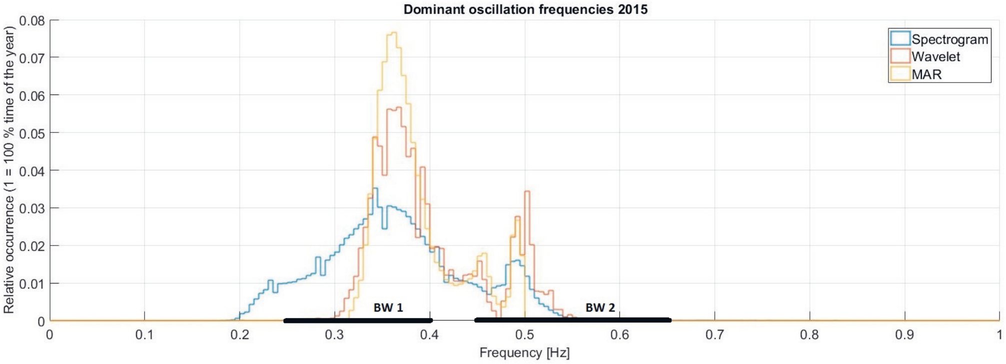

Figure 2. Dominant oscillation frequencies in 2015 and the selected bandwidths BW 1 and BW 2 according to the dominant modes.

Based on the results shown in Figure 2, the oscillations were divided into two bandwidths. Bandwidth 1 (BW 1, 0.25 – 0.40 Hz) was selected to monitor the characteristics of the 0.33 Hz inter-area oscillation mode between Finland and Sweden, which is assumed to be present in the system all the time. The upper frequency limit was selected so that the bandwidth has 50 mHz margin to the higher oscillations, which are observed with the frequency values exceeding 0.45 Hz.

Bandwidth 2 (BW 2, 0.45 – 0.65 Hz) was selected to monitor the oscillations close to 0.5 Hz. Figure 2 shows that there might be multiple oscillation modes within this bandwidth but it is difficult to distinguish different modes from each other as the frequencies are close to each other. As the purpose is to analyse the situations when the oscillations with higher frequencies occur, the frequency band for Bandwidth 2 was considered to be sufficient as the characteristics of the studied oscillation frequencies are not known and calculating oscillation levels at different bandwidths requires significant computational efforts.

The results also show that the frequency bands estimated using Wavelet and MAR methods are narrower than the frequency bands estimated using spectrograms. On the other hand, spectrogram parameters were intentionally selected so that it is not so sensitive for sudden and short term variations in oscillation frequencies. Also, during the analysis it was seen that MAR and Wavelet methods tend to easily change estimated mode frequency when both bandwidths were present. For this reason, the further analysis was performed using only spectrogram results, which were not so sensitive for oscillation frequency variations.

The oscillation levels of the Bandwidths 1 and 2 were calculated every 30 seconds using 15-minute spectrograms. Figure 3 presents the distribution of the calculated oscillation amplitudes of Bandwidth 1 (0.25 Hz – 0.40 Hz) and the corresponding cumulative density function in 2015. The figure also shows log-normal probability distribution fit of the data and the calculated cumulative density function of the oscillation amplitudes. The results presented show that amplitudes of the oscillations at bandwidth 0.25 – 0.40 Hz fit well to the lognormal distribution. The figure also shows the amplitude levels, which correspond to the 85 % (11.1 MW), 90 % (12.1 MW) and 95 % (13.7 MW) cumulative probability values calculated using the lognormal distribution.

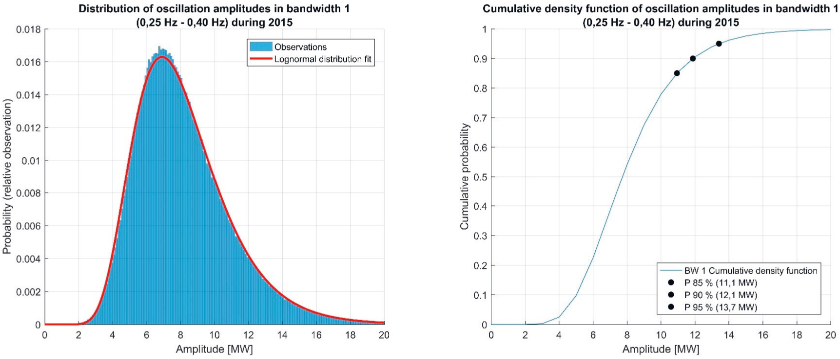

Figure 3. Distribution and cumulative density function of amplitudes of the 0.25–0.40 Hz bandwidth (Bandwidth 1).

Calculated statistical indicators can be used for analysing the cases when the oscillation levels are higher than usually. This enables understanding how the characteristics of the system change as a function of the seasonal and operational parameters. By comparing the results between different years, it is also possible to summarize the changes in power system characteristics between different time of the day, day of the week and season of the year.

4.2 DETECTED SEASONAL VARIATIONS IN OSCILLATION LEVELS

Figure 4 presents the observations of the oscillations at 0.25–0.40 Hz bandwidth during 2015. The figure illustrates the average number of minutes in each operating hour of the week when the oscillation amplitude levels have been higher than the 90 % of the oscillations during the year as a function of week of the year and operational hour. The operating hours are presented separately for working days and weekends.

The variations of oscillation levels during 2016 were analysed in a similar way as the variations in 2015. However, in order to enable comparing the results between the years 2015 and 2016, the oscillation levels during 2016 were analysed using the statistical results from the year 2015. Thus, the results show the observations during 2016 when oscillation levels have been higher than 90 % of the time using the limits calculated with 2015 statistical data. The results are shown in Figure 5.

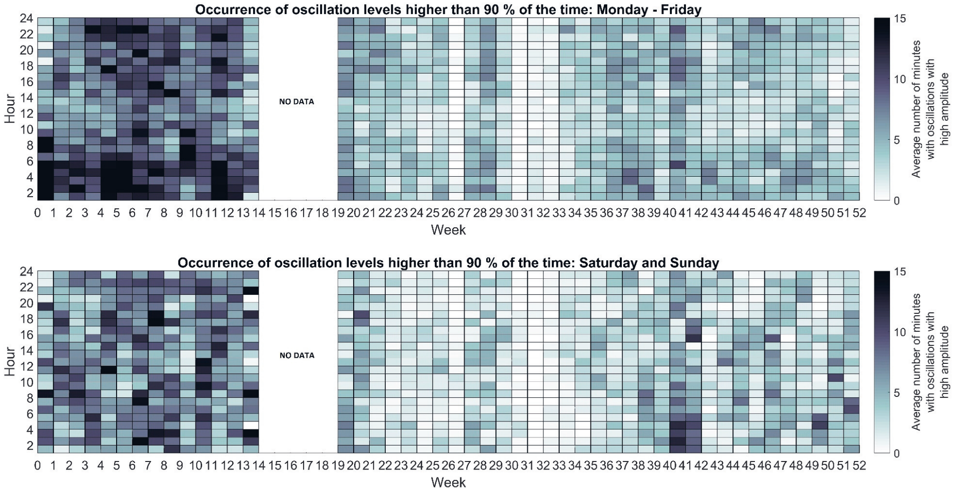

Figure 4. Occurrence of oscillation events higher than 90 % (12.1 MW) of the observations at Bandwidth 1 (0.25 Hz – 0.40 Hz) in 2015.

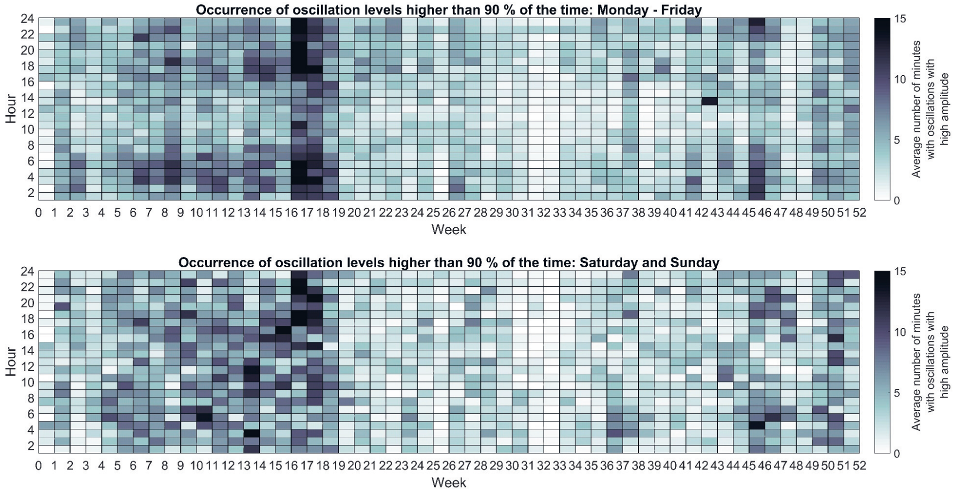

Figure 5. Occurrence of oscillation events higher than 90 % (12.1 MW) of the observations at Bandwidth 1 (0.25 Hz – 0.40 Hz) in 2016.

Figures 4 and 5 show that the oscillations at the Bandwidth 1 are present all the time over the year and the oscillations tend to be stronger during winter night hours. In both years, the oscillation levels at Bandwidth 1 tend to decrease as the season changes from winter towards summer. However, the results indicate that the oscillation levels were higher during 2015 than 2016.

Oscillations at Bandwidth 2 are not present all the time in the PMU measurements. For this reason it is more difficult to make statistical analysis of the amplitude distribution of the oscillation mode. Thus, the statistical limits calculated for the Bandwidth 1 are used to analyse also Bandwidth 2. Figure 6 and Figure 7 present the oscillatory characteristics of the Bandwidth 2 during 2015 and 2016. The figures show the occurrence of the observations when the oscillation amplitude is higher than 90 % compared with the oscillation amplitudes of Bandwidth 1.

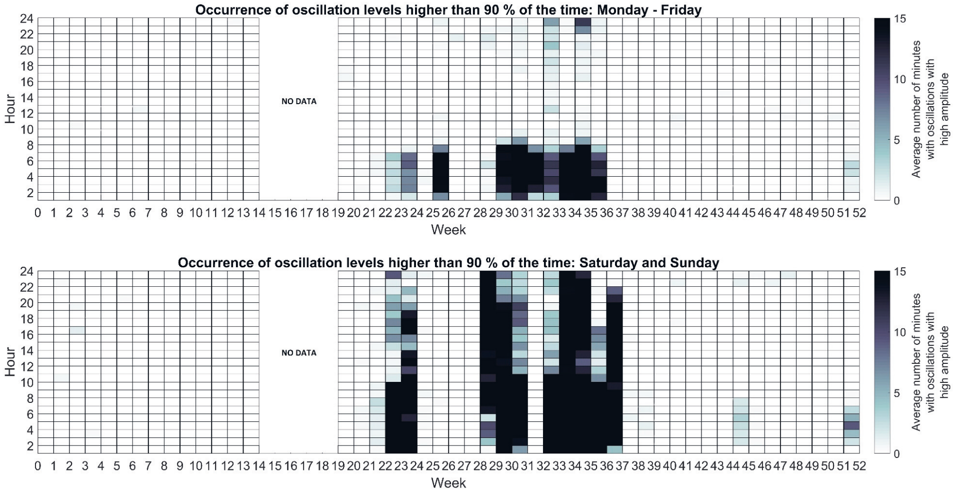

Figure 6. Occurrence of oscillation events higher than 90 % (12.1 MW) of the observations at Bandwidth 2 (0.45 Hz – 0.65 Hz) in 2015.

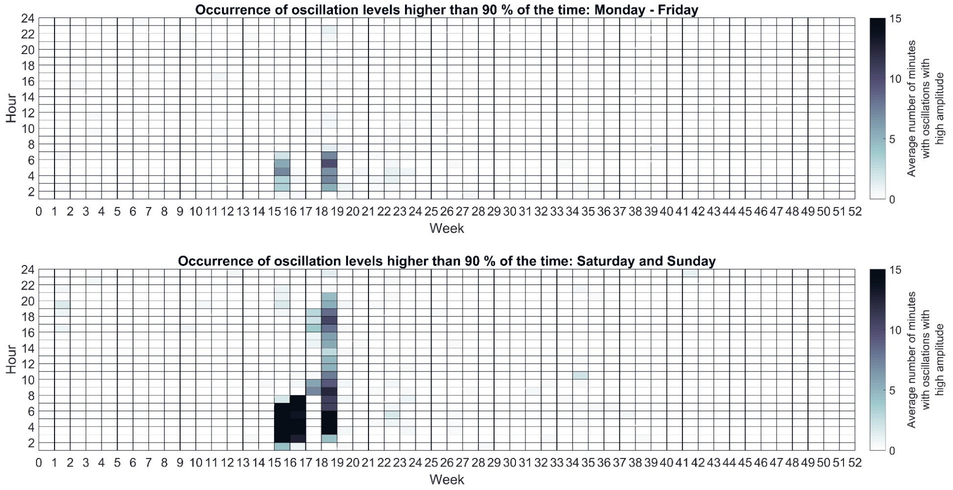

Figure 7. Occurrence of oscillation events higher than 90 % (12.1 MW) of the observations at Bandwidth 2 (0.45 Hz – 0.65 Hz) in 2016.

The results in Figures 6 and 7 show that the oscillations at 0.45 – 0.65 Hz frequency bandwidth seem to appear during the summer in 2015 and there were only few observation of the mode in 2016. Furthermore, oscillation events seem to concentrate especially to summer weekend nights in 2015.

5 DISCUSSION

The results (Figures 4 and 5) show that the oscillation at Bandwidth 1 (0.25–0.40 Hz), representing the well-known 0.3 Hz inter-area oscillation mode, is present all the time in the system as expected. The oscillation levels are higher during winter night when there are more generators in the system and there are times when power is momentarily exported from Finland to Sweden. The results also show that there are time periods when oscillations at Bandwidth 2 (0.45–0.65 Hz), representing the 0.5 Hz oscillation, have higher amplitude than oscillations at Bandwidth 1 and that these oscillations are not present all the time in the system. Oscillation events at Bandwidth 2 were observed especially during summer nights in 2015. However, less oscillations at Bandwidth 2 appeared in 2016. Thus, in order to be able to analyse the root cause of the oscillations better, it is important to understand how the operational parameters of the system change between the years.

In the Nordic power system the consumption is the highest during the winter when the heating and illumination increase the consumption. During the spring, there is usually a lot of hydro power which increases the power transmission in some parts of the system. In addition, the revisions of the large thermal generators and HVDC connections are typically in the summer. Hydro power plants, on the other hand, have revisions depending on the water situation. Figures 8 and 9 present power generation levels in Finland in 2015 and 2016 as a function of week of the year and operational hour. There are periods during summer nights when power generation levels are low. In 2015, these were the times when the 0.5 Hz oscillations occurred. This would indicate that the system would be more sensitive to the 0.5 Hz oscillations when there are not that much production in the system and the system inertia level is low. However, the results show that the power generation levels are low also during 2016 when there were only few oscillation events. In addition, the correlation between the 0.5 Hz oscillations and the synchronous system inertia and the Finland–Sweden power transfer was analysed, but any unambiguous correlation was not found.

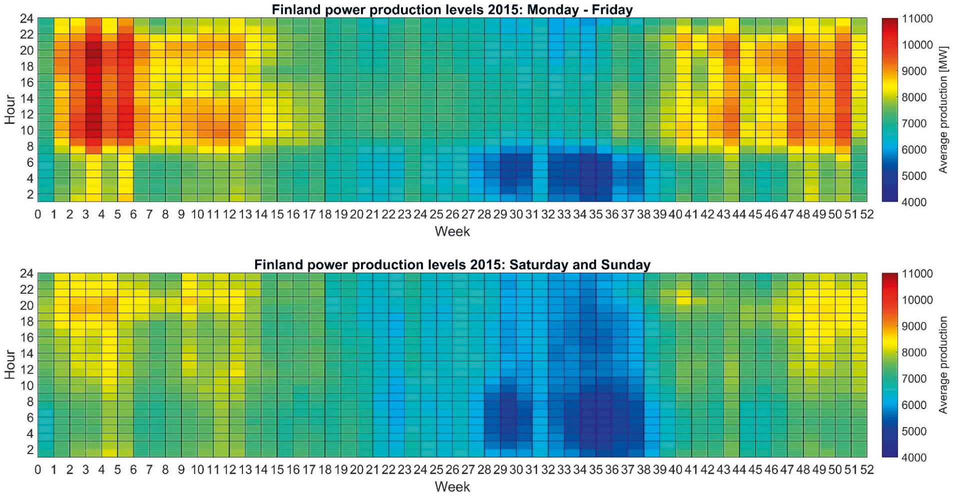

Figure 8. Power production levels in Finland in 2015.

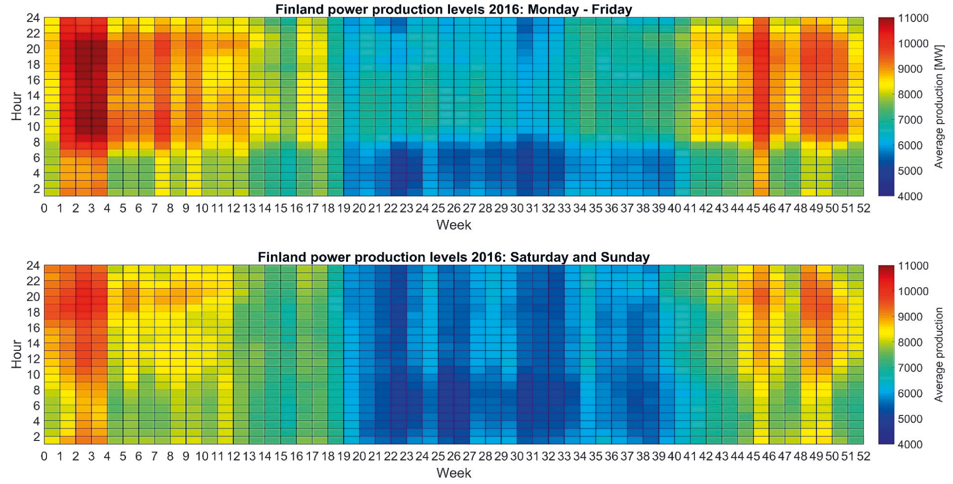

Figure 9. Power production levels in Finland in 2016.

It is important to continue the analysis and obtain data from even longer time periods to understand in which cycles the oscillations occur. More data from different parts of the system are needed in order to be able to locate the source of the oscillations. Applying signal processing methods such as spectrograms and damping estimation methods in power system requires good understanding of the modal characteristics of the power system and their seasonal variations. Other oscillation modes in the system might also affect the modal analysis results.

6 CONCLUSIONS

This paper presented a process for analysing seasonal oscillatory characteristics of the Nordic power system using PMU measurements from the ac-interconnection between Finland and Sweden in 2015 and 2016. The paper used spectrograms and modal identification methods to analyse dominant oscillation modes. The oscillation levels during the different seasons were calculated using spectrograms and then the oscillation level trends and variations were analysed statistically.
Using the process described in the paper it is possible to identify the dominant oscillation modes and then statistically analyse the characteristics of the oscillation modes over long time periods. The

process also provides more information on the 0.5 Hz oscillations from the Finnish perspective. The well-known 0.3 Hz oscillation mode (represented by Bandwidth 1, 0.25–0.40 Hz) was present during the whole period, as assumed, and the oscillation amplitudes tend to be the largest during winter nights. In addition, there are occasionally oscillations at the 0.5 Hz frequency (represented by Bandwidth 2, 0.45–0.65 Hz) even when power is imported from Sweden to Finland. The oscillations appeared especially during summer nights when there were less generators in the grid. However, yearly variations are large and more data and analysis from the power system over even longer time periods are needed in order to analyse further the correlation between the oscillation events and operational parameters of the system.

The oscillatory characteristics of the system vary between different days and months and also different years could be very different although the power transfer conditions seem to be similar. Thus, when signal processing methods, such as spectrograms and modal identification methods, are used to analyse power systems, it is important to validate systematically the parameters used by the methods. Understanding the long-term characteristics of the oscillation modes requires analysis performed over multiple years and the results from the long-term analysis could also serve the transmission system planning to provide information how the system characteristics have developed during the years.

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