Electrical disturbances in nuclear power plants and their simulation requirements

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Abstract of the master's thesis

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Abstract

Electrical systems perform various functions in a nuclear power plant (NPP), and they are required for the operation of many safety systems. In normal operation, all electrical systems are connected together at the high voltage level, which creates the potential for common cause failures due to faults in the plant internal or external power system. In fact, several such incidents have been reported. This thesis reviews literature related to NPP electrical system reliability and electrical disturbances. Three particularly relevant conditions (power frequency overvoltages, open phase conditions and subsynchronous oscillations) are selected for in-depth analysis. Based on the literature review and analyses, this thesis makes recommendations about simulating these conditions in COSI. COSI is a research project which aims to develop a co-simulation platform for simulating the electrical system and NPP process systems together. This thesis notes that existing electrical simulation studies have not considered process system feedback effects and other transient dynamics in much detail, and that COSI could provide insight into their effects on nuclear safety.

Keywords nuclear power plant, electrical system, disturbance, reliability, co-simulation

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Tiivistelmä

Sähköjärjestelmät ovat tärkeitä lukuisille ydinvoimalaitoksen toiminnoille. Muun muassa monien turvallisuusjärjestelmien toiminta riippuu sähköjärjestelmistä. Normaalissa käyttötilanteessa kaikki sähköjärjestelmät kytkeytyvät yhteen suurjännitetasolla, mistä aiheutuu mahdollinen yhteisvikariski, jos laitoksen sisäisessä tai ulkoisessa sähköverkossa tapahtuu vika. Useita tämänkaltaisia tapahtumia onkin raportoitu. Tässä diplomityössä tehdään katsaus kirjallisuuteen, joka liittyy ydinvoimalaitosten sähköjärjestelmien luotettavuuteen ja sähköjärjestelmän häiriöihin. Kolme erityisen oleellista häiriötyyppiä (verkkotaajuiset ylijännitteet, vaihekatkokset ja alisynkroniset värähtelyt) valitaan lähempään tarkasteluun. Kirjallisuuskatsauksen ja tarkastelujen perusteella annetaan suosituksia näiden häiriöiden simuloimiseen COSI-projektissa. COSI on tutkimusprojekti, jossa kehitetään kosimulaatioalusta sähköjärjestelmän ja ydinvoimalaitoksen prosessijärjestelmien yhteissimulointiin. Työn mukaan aiemmissa sähköjärjestelmien simulointitutkimuksissa ei ole tarkasti selvitetty prosessijärjestelmistä aiheutuvia takaisinkytkentöjä tai muita transienttivaikutuksia. COSI voisi parantaa ymmärrystä näiden vaikutuksista ydinturvallisuuteen.

Avainsanat ydinvoimalaitos, sähköjärjestelmä, häiriö, luotettavuus, kosimulaatio

Contents

Abbreviations

COSI	Co-simulation model for safety and reliability of electric systems in flexible environment of NPP (research project)
EDG	emergency diesel generator
ESSI	Electric Systems and Safety in Finnish NPP (research project)
HVAC	heating, ventilation and air conditioning
HVDC	high voltage direct current
IAEA	International Atomic Energy Agency
I&C	instrumentation and control
LOCA	loss of coolant accident
LOOP	loss of offsite power
NEA	OECD Nuclear Energy Agency
NPP	nuclear power plant
OECD	Organisation for Economic Co-operation and Development
OPC	open phase condition
PSA	probabilistic safety assessment
SAFIR2022	Safety of Nuclear Power Plants – Finnish National Research Programme 2019–2022
SBO	station blackout
SSCI	subsynchronous control interaction
SSO	subsynchronous oscillations
SSR	subsynchronous resonance
SSTI	subsynchronous torsional interaction
TSO	transmission system operator
UPS	uninterruptible power supply

1 Introduction

Electrical systems perform several functions in a nuclear power plant (NPP). These functions include generation and transmission of electrical power, distribution of power to process and control systems, and operation of various safety systems [1]. As almost every feature in an NPP directly depends on electrical systems, the reliability of these systems is considered to have a large impact on the economics and safety of a plant. Indeed, for safety reasons, electrical systems in NPPs follow typical NPP design principles, including redundancy, diversity and separation.

Several incidents in NPPs around the world have illustrated the role of electrical systems in safety. In some cases, electrical issues inside the plant or in the external grid have triggered unforeseen common cause failures in safety related equipment. These failures have compromised the defence-in-depth and redundancy properties of the plants, and shown that certain conditions may not have been adequately considered in their design. These incidents have been documented in operational experience databases and analysed in various reports according to the principle of continuous safety improvement.

This thesis is part of a research project called Co-simulation model for safety and reliability of electric systems in flexible environment of NPP (COSI), which itself is part of the Finnish National Research Programme on Safety of Nuclear Power Plants 2019–2022 (SAFIR2022). The COSI research project aims to develop a detailed co-simulation model, which can be used to analyse interactions between electrical systems and other plant components as a function of time under various circumstances [2]. This model can be used to simulate conditions such as those that caused the aforementioned incidents. The simulations would provide details about the effects of these conditions, and could help to decide what kind of mitigative measures are needed, if any.

In this thesis, literature related to NPP electrical systems is reviewed. The literature focusses on electrical system reliability, electrical disturbances and simulation of electrical systems. This thesis does not attempt to analyse incident reports directly. Instead, it reviews various reports that have already analysed and categorised entries from operational experience databases.

Based on the literature reviewed, the incidents discussed therein, previous work in the ESSI project, as well as the COSI project plan, three conditions that are recognised as particularly important and relevant are analysed in detail. These conditions are power frequency overvoltages, open phase conditions and subsynchronous oscillations. Based on the literature review and an analysis of these conditions, this thesis describes the current state of research on these topics, and makes recommendations about simulating the conditions in COSI.

Section 2 of this thesis describes background information and reviews literature related to electrical systems in NPPs. Section 2.1 briefly describes the role of electrical systems in an NPP and the design principles applied to them. Section 2.2 reviews previous work done under the SAFIR programme and introduces COSI and co-simulation in more detail. Sections 2.3 through 2.5 review literature related to electrical systems and disturbances in general, while Sections 2.6 and 2.7 describe certain specific requirements related to NPP electrical systems.

Sections 3 to 5 discuss the three electrical conditions in more detail. Each section introduces the respective condition and any relevant theory, followed by a review of literature specifically related to that condition, and a description of a typical real world event where the condition occurred. Each section concludes with a discussion of previous research into the condition and relevance to COSI. Finally, Section 6 ends the thesis with final conclusions and a summary of the topics discussed.

2 Background and literature

2.1 General

Used nuclear fuel contains a significant amount of radioactive fission products, and it is important that these compounds are kept sealed inside the fuel. Indeed, the entire design philosophy of nuclear power facilities is centred around keeping the fuel intact and preventing the release of radioactive material. Nuclear power plant systems are designed according to the defence-in-depth principle, where several different functional layers work independently to ensure safety. On a high level, these layers include the fuel structure and fuel cladding, the primary circuit, and the containment building. Radioactive material would have to work its way through all the layers to be released from the plant. [1]

More specific design philosophies, applied to the design of safety critical systems, are redundancy, diversity, separation, fail-safety and automatic startup. In a redundant system, functional parts are duplicated such that a single failure does not prevent the operation of the system's functions. In NPPs, this principle is usually applied in a way that allows two parts of the system to be under maintenance or fail without affecting functionality (Figure 1, left). Diversity means that a function is implemented by several fundamentally different redundant parts, such as two different types of pumps (Figure 1, centre). This is done to reduce the probability and impact of common cause failures. Separation means that redundant systems or parts are physically or functionally separated to prevent common cause failures due to events such as fires, floods or electrical disturbances (Figure 1, right). [1]

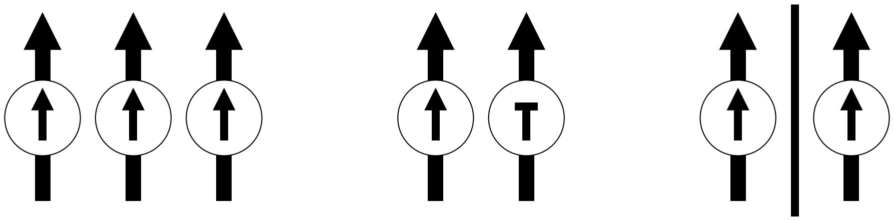

Figure 1: Design principles for safety systems: redundancy (left), diversity (centre), separation (right).

A fail-safe system is designed such that it enters a state that is most likely to be safe, in case the system fails or loses electrical power, and in other similar situations. This could mean entering a specific state for a valve, or activating a safety function for an automation system. Finally, the automatic startup principle means that safety systems activate automatically, so that no operator actions are required for a certain amount of time after any kind of event. The length of the time period could be 30 minutes, for example. Automatic startup reduces operator pressure and ensures that operators have time to judge which actions are the most appropriate in a given situation. [1]

Electrical systems perform several different functions in an NPP. One of the main functions is to generate electrical power and transmit it from the generator towards the electrical grid. A second function is to provide power to systems which are required for the operation of the plant and its processes. These include various pumps as well as auxiliary systems for purposes such as cooling and lubrication. All instrumentation and control (I&C) systems, automation systems, and many actuators are also powered by electrical systems. Importantly, almost all safety related systems also rely on electrical power for operation. [1]

As electrical systems serve important purposes and form the backbone of the whole plant, their reliability is considered to be important for the safety of the plant. Issues in electrical systems can potentially affect the entire plant through common cause failures, as many redundant parts are ultimately supplied from the same electrical source. Therefore, electrical systems and components are designed according to the principles discussed above. However, various incidents related to electrical systems have been reported from NPPs over the years. These incidents have called into question certain assumptions made in the design of the electrical systems in many operating plants.

2.2 SAFIR

The Finnish National Research Programme on Safety of Nuclear Power Plants (SAFIR) is a continuing series of four-year research programmes initiated by the Ministry of Economic Affairs and Employment (TEM). The purpose of the programme is to maintain and develop expertise in the field of nuclear safety. The programme is based on legislation in the Finnish Nuclear Energy Act, and it is mostly funded by the State Nuclear Waste Management Fund (VYR). [3]

The previous SAFIR programme, SAFIR2018, included the Electric Systems and Safety in Finnish NPP (ESSI) research project. The purpose of this project was to research phenomena, impacts and mitigation methods for issues caused by open phase conditions (OPC), large lightning strikes and flexible operations. The project produced several reports and articles on these topics. [4]

Kulmala [5] reviewed literature for a general overview of OPCs and how different electrical configurations (e.g., transformer connections and grounding) affect OPCs. They also discuss the general structure of the electrical system in an NPP. They list several OPC incidents, and identify that the incidents can be divided into cases where the OPC occurred on a connection that was actively feeding power to the plant, and cases where the OPC occurred on an unused backup connection and went unnoticed for some time. They briefly discuss how OPCs affect different plant components, and how plants are currently equipped to deal with OPCs. They interviewed plant operators as well as the transmission system operator (TSO) and the nuclear regulator to evaluate the preparedness of Finnish NPPs against OPC.

Kulmala and Alahäivälä [6] expand on the previous report, providing more details on the topics discussed previously. In particular, they concentrate on the effects of OPC in the NPP electrical system, and on the detection of OPCs. They note that the most severe and therefore the most important fault locations are the generator bus, the primary side of the unit transformer and the primary side of the standby transformer. They again interviewed the plant operators, the TSO and the regulator. They conclude that Finnish NPPs are well prepared against OPC and that no critical safety issues were discovered. The findings are also summarised in a conference paper [7].

Alahäivälä and Lehtonen [8] studied the effects of OPCs on small induction motors in simulation and laboratory settings. They found that the simulation results correspond well to analytically solved values. The laboratory results display similar phenomena as the simulations, but with certain differences in values due to the simplified model used. The laboratory results indicate that the available torque from the motor decreases significantly during an OPC, and that the motor can operate at least for a few minutes during an OPC without overheating.

Rizk et al. [9] studied large scale grounding systems of power plants using computational methods. They calculated the transient electromagnetic effects of a lightning strike to an electrical transmission tower near such a grounding system. They note that earlier studies have found soil inhomogeneity and soil ionization to affect the results significantly. Their model additionally considered high soil resistivity, typical of rocky and sandy soil, and the effects of a nearby body of water. They found that the nearby sea strongly affected the lightning response of the grounding system.

Subedi and Lehtonen [10] analysed how lightning overvoltages are transmitted through transformers in power plants. They used a simulation method where the transformers were modelled using an equivalent circuit with values from frequency response measurements. They varied which voltage levels had surge arresters installed, and found that all surge arresters significantly reduced the overvoltages transmitted to the medium voltage levels. Gürbüz [11] also simulated the effects of lightning on power plants in their Master's thesis. They based their models on real NPP electrical systems and modelled the system in more detail. Pasonen [12] studied the effects of lightning transients on low voltage AC and DC systems in NPPs. They simulated how the model responded to the transients from Subedi and Lehtonen, and how overvoltage suppression devices, capacitors and batteries in the low voltage system affected the response.

Lehtonen, Schürhuber and Pichler [13] again simulated lightning transients in a power plant environment. They focussed on ground potential rise and the effects on low voltage signalling cables. They found that significant overvoltages would occur, which would damage the signal cables, and that preventing such overvoltages would require detailed analysis and planning in the design of the grounding system.

Pasonen [14] investigated flexible operation of NPPs in Finland by interviewing the plant operators and the nuclear regulator, and by reviewing literature. Flexible operation includes load following, balancing, ancillary services and other power adjustments. According to the interviews, no electrical system issues or legal issues prevent flexible operation. However, flexible operation is not currently practised or planned in any NPPs in Finland due to lack of need and interest. Flexible operation would necessitate some changes to automation and control systems as well as operating procedures and training, but no fundamental issues prevent it. Flexible operation is currently practised in a few countries.

Pasonen [15] also reviewed literature to consider NPP flexible operation from a grid and market perspective. They found several reports and articles on topics related to this. Additionally, they briefly analysed the potential performance of NPPs in a balancing market using past market data. Finally, they interviewed the TSO, who indicated that NPPs do not currently participate in flexible operation, but that the value of flexibility may increase in the future.

Holmberg [16] approached NPP flexible operation from a risk analytic perspective, summarising the risks and benefits of such operation and developing a risk analysis framework. In future research, this framework could be developed further and used as a basis for considering realistic decision options.

During the research done under ESSI, a need for more detailed simulations and further studies of NPP electrical systems was identified. Ideally, it would be possible to simulate behaviours and interactions between the external electrical grid system, the plant internal electrical system, and the plant automation, thermal hydraulic and reactor physical systems. At present, electrical grid simulations only model NPPs as simple generators. Similarly, plant level simulation systems only have a simplified model of the internal electrical grid, and typically model the external grid as a fixed voltage source. Therefore, to better understand electrical events that are important for NPP safety, a new simulation model would be needed. [2]

The Co-simulation model for safety and reliability of electric systems in flexible environment of NPP (COSI) research project is part of the latest SAFIR2022 programme. COSI aims to develop a detailed simulation model of the external and internal electrical systems that interfaces with existing automation, thermal hydraulic and reactor physics models. The models could then be co-simulated to analyse in detail how various electrical phenomena interact with plant systems. The aim is to evaluate the adequacy and balance of safety requirements for plant systems with regard to electrical disturbances, and even reach an understanding on the set of electrical system initiating events that should be included in the safety analysis of an NPP. COSI continues the work on OPCs and flexible operation started in ESSI. However, lightning strikes have been excluded from COSI due to the very different timescales involved. [2]

Detailed simulation models already exist for NPP automation, thermal hydraulic and reactor physics systems. These models are implemented in software such as APROS, and they are used for safety analysis and training. Similarly, detailed models exist for the electrical grid. However, these models are implemented in entirely different simulation software that is suitable for electrical grid simulation but not power plant process simulation. Similarly, the opposite is true for power plant process simulation. Therefore, the intention of the COSI project is to combine different simulation platforms into a single simulation environment using co-simulation methods. [2]

In co-simulation, two or more simulation tools are coupled into a single simulation environment. The tools exchange data only at predefined points, and otherwise each simulation is solved independently. Therefore, the different simulation platforms and models can essentially act as black boxes, and can be developed independently without having to consider the entire coupled system. This kind of approach can simplify and accelerate development of simulation models in interdisciplinary environments. Typical applications include the automotive industry, HVAC systems, and electricity production and distribution. In electrical systems, co-simulation has been applied to simulation of power grids and communication systems in particular. However, an application of co-simulation to subsynchronous resonance (SSR) modelling was also identified. [17]

2.3 DIDELSYS

The OECD Nuclear Energy Agency (NEA) formed a task group to investigate Defence in Depth of Electrical Systems and Grid Interaction with nuclear power plants (DIDELSYS). The task group was formed as a result of findings related to the 2006 Forsmark event. The objectives of the task group were broad, including evaluating the robustness of electrical systems in NPPs, evaluating the principles of designing such systems, evaluating the methodologies used to analyse the safety of such systems, and evaluating the interactions between NPPs and the electrical grid. The task group produced a report [18] containing an analysis of relevant incident reports as well as discussions of 12 separate technical issues.

The DIDELSYS task group screened the IAEA/OECD/NEA Incident Reporting System (IRS) database and the US Nuclear Regulatory Commission (NRC) Licensee Event Reports for incidents related to electrical systems. The group identified 88 and 19 relevant reports from these sources respectively. In the DIDELSYS report, these events are categorised according to several criteria. The analysis displays the expected results that failures in large power supplies mostly cause plant trips, and that failures in instrument power supply often lead to failure of accident mitigation systems. Analysis of the causes and contributing factors of the events shows that certain factors, such as human errors and electrical protection malfunctions, are more common than other causes, but that no factors dominate over the others. The report briefly describes several example events for each cause, but no plants or incidents are identified by name. [18]

The 12 technical issues discussed in detail in the DIDELSYS report are:

- grid challenges
- communication between NPP and grid operators
- house load operation
- power supply of protection and control systems
- design of high reliability electrical systems
- fail safety
- challenges in failure mode and effects analysis (FMEA)
- conflicts between protection and reliability
- protection of safety buses
- digital protective relays
- power supply of operator information systems
- operator response to electrical events.

These topics are broad in scope and sometimes overlapping, so it is not feasible to summarise them all. Nevertheless, to highlight a topic that has particular relevance to COSI, the report notes that there are challenges in failure mode and effects analysis (FMEA) of electrical systems. Existing industry standards may incorrectly give the impression that all possible failure modes are covered by analysing a few simple types of electrical faults. Design deficiencies arising from these challenges have likely contributed to incidents such as in 2006 at Forsmark. The report notes the difficulty of analysing the effects of faults without the use of simulation tools, and suggests that electrical system simulation tools should be developed and verified to such extent that they can be used for safety analysis, similarly to existing fuel cladding temperature or loss of coolant accident (LOCA) simulations. The report recommends tools such as Matlab/Simulink for modelling the onsite electrical system. [18]

Later, the DIDELSYS task group produced another report [19] which briefly discusses the same topics. Additionally, it details the results of a survey on the actions taken by operators and regulators as a result of the 2006 Forsmark and 2008 Olkiluoto events. Most countries had considered some aspects of these events relevant and applicable.

2.4 ROBELSYS

As a result of the 2011 Fukushima Daiichi accident, the NEA again formed a task group, to investigate the Robustness of Electrical Systems of NPPs in Light of the Fukushima Daiichi Accident (ROBELSYS). A new task group was needed, as the causes and effects of the accident were considered to be beyond the scope of previous investigations, including DIDELSYS. The task group held a workshop to provide a venue for sharing information about design and simulation of safety related electrical systems. As a result, a paper [20] was published, summarising the contents and conclusions of the workshop. The conclusions include recommendations to:

- provide standards for addressing beyond design basis events
- provide standards on diversity in electrical systems
- develop simulation tools for simulating asymmetric 3-phase faults
- develop new standardised transient waveforms
- investigate the use of probabilistic safety assessment (PSA) to analyse the effects of different power sources.

Several of the papers presented in the ROBELSYS workshop are relevant to COSI. In their paper, Kanaan describes the modernisation project of Oskarshamn 2. The project included detailed simulations of the electrical system using the Simpow software. The simulations were mainly concerned with the adequacy of the electrical systems during load, motor startup and short circuit. All necessary component data was not available, so measurements had to be performed to acquire certain parameter values. The project also studied how grid disturbances affect plant internal systems. “All” short circuit and ground fault cases were examined, and based on the results, a small number of voltage and frequency profiles were developed which were used for specification, testing and safety acceptance. [20]

No further details on this topic are provided in the paper. However, the earlier DIDELSYS report [18] contains descriptions of disturbance profiles provided by Oskarshamn, which are presumed to be the same. There are 13 different profiles, representing faults such as load rejection, shunt faults in lines and busbars cleared by both normal and backup protection, and wide area system disturbances. The profiles are developed as worst case scenarios and do not exactly replicate any specific faults.

Geissler discusses mitigation of beyond-design-basis events in electrical systems. In their paper, they list different types of grid voltage and frequency variations, dividing them into faults standardised in grid codes and faults not standardised. Standardised failures include (a) slow voltage variations, caused by reactive power or load flow issues; (b) fast/transient voltage variations, caused by short circuits, switch-overs or lightning strikes; and (c) frequency variations caused by active power imbalances. Non-standardised failures include (d) fast transients, i.e., lightning, switching, arcing, transmission line phenomena, resonance, electromagnetic pulses and geomagnetically induced currents; as well as (e) other failures, including ground faults and phase interruptions. [20]

Richard describes the process of verifying and validating a simulation tool for analysing NPP systems. They note that one should use simulation tools when the physical phenomena to be studied are complex or numerous, and when it is necessary to have significant computing resources. According to Richard, the process of selecting a simulation tool should start with clearly identified requirements followed by a precise, written technical specification. The paper also lists different electrical phenomena based on their timescales (Figure 2) and suggests simulation software for different regions on this scale, with EMTP-RV and PSCAD suggested for phenomena ranging from 1 MHz to 1 Hz, and Eurostag, ETAP and PSS-E for 10 Hz and lower. [21]

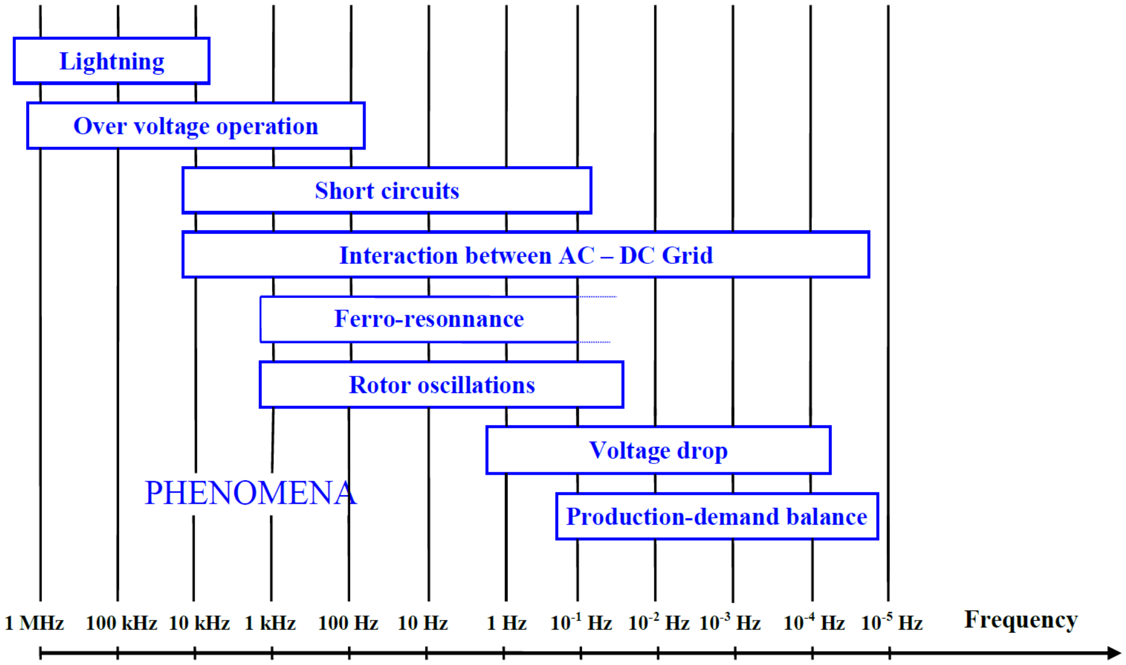

Figure 2: Electrical phenomena and their timescales according to Richard. [21, p. 6]

Svensson et al. propose a procedure for grid interaction analysis. The presented procedure has been used to analyse the propagation and effects of electrical transients in the three units at Oskarshamn. The procedure is based on disturbance profiles, where simulations are performed for a multitude of different events and scenarios, which are then grouped and condensed into a select few reasonable worst case profiles. These profiles can then be used to ensure that equipment can withstand the stress caused by the disturbance, or that protection will disconnect the equipment. The authors note that disturbance profiles are currently not commonly used in the nuclear industry, but that examples from other fields include standardised lightning impulses and grid fault ride-through profiles. [21]

In their paper, they discuss four types of faults, describing their causes and effects in the electrical grid. The first condition discussed is load rejection, where the generator is suddenly disconnected from the grid. This typically causes a temporary power frequency overvoltage on the generator bus, which propagates into any connected equipment. The second type of fault are shunt faults, such as short circuits and ground faults. These conditions cause a significant voltage drop until the fault is cleared, and some type of voltage recovery after this. The authors note that faults in different locations in the grid as well as extended clearance times due to backup clearance should be considered. Additionally, they note that sudden phase shifts and their effects on power electronics devices should be carefully considered. The third condition discussed is loss of generation, which causes a frequency drop in the electrical system. Finally, the fourth condition is voltage instability, where insufficient transmission capacity causes a slow or fast voltage collapse in a large area. The authors note that their analysis does not consider open phase conditions, which have since been recognised as a relevant type of fault. [21]

Lamell discusses electrical simulation activities at Forsmark. First, they describe four incidents which have inspired some of this simulation work. The incidents include the 2006 event, which was caused by a power frequency overvoltage transient after a short circuit; an event in 2008 where a three phase short circuit fault in the off-site grid caused main circulation pumps to trip due to phase angle deviation; a 2012 event where a lightning strike caused damage to power electronics components; and a 2013 open phase condition (OPC) event, where safety functions failed due to the OPC but the fault was not automatically disconnected. [21]

The paper also describes what kinds of electrical simulations were performed for the original safety analysis of the units, and finally, what kinds of simulations have been performed more recently. The original simulations were performed using an old simulation tool, and the scenarios were limited to a single grid disturbance case as well as startup and short circuit simulations. More recent simulations have been performed with Simpow, and most recently with PowerFactory. Simulated scenarios include off-site grid short circuits and ground faults, behaviour of motors during slowly decreasing network voltage, short circuit power requirements in the auxiliary grid connection, and finally, various open phase conditions. Future work is said to concentrate more on discovering new fault types and scenarios, as many of the incidents described were not considered before they occurred. The authors note that the necessary data for the simulation models can be hard to obtain, a concern also expressed by Kanaan for Oskarshamn above. [21]

Kim and Jeong describe electrical simulation studies applied in the design of

Korean NPPs. The studies consist of power system adequacy (load flow and voltage profile), motor startup, and short circuit simulations in several different operational states, such as normal operation, standby, loss-of-coolant (LOCA) and station blackout (SBO). The simulations are performed using the ETAP software. The authors note that other studies are also performed, but they are not described in the paper. These include protective relay coordination studies, power system harmonics analyses and DC system analyses. [21]

Khandelwal and Bowman discuss the simulation of open phase conditions (OPC). Investigation into OPCs was inspired by two separate events in Byron in 2012. In one of the events, the OPC was not detected automatically and caused safety related and other components to trip, similarly to the 2013 Forsmark event. Several factors affect how an OPC presents in an NPP electrical system. These factors include the plant state, transformer construction, various induction motor parameters, transformer loading, fault location and ground impedance of the open phase. The authors point out that accurate transformer and motor data is essential for accurate simulation results. Additionally, an accurate model of the electrical system provides much better accuracy than a simplified model. [21]

The authors note that there are two aspects to OPC analysis: acceptability, which is the ability to function during an OPC, and detectability, which is the ability of protection systems to detect the OPC and disconnect the fault. The effects of two factors on the acceptability and detectability of OPC is illustrated in Figure 3. The factors considered are the ground impedance of the open phase and the transformer loading factor. The dark green area represents an acceptable OPC and the light green area a detectable OPC, while the yellow and red areas represent situations where problems are expected. One of the findings of the study is that detection of OPCs can be difficult or impossible in some cases, particularly with only phase voltage measurements. [21]

2.5 Other literature

Duchac and Noël describe the 2006 Forsmark event and what can be learned from it. Additionally, they present a review of relevant incident reports from the IAEA/OECD/NEA Incident Reporting System (IRS) database as well as the US Nuclear Regulatory Commission (NRC) Licensee Event Reports. The review appears very similar to the review in the DIDELSYS report, but more incidents are included here, with 120 and 19 reports from the IRS and NRC respectively. The conclusions of the review are the same as in DIDELSYS. The authors note that as reporting events to the IRS is voluntary, all events may not be reported, with certain types of events affected more. For example, they suggest that grid disturbances may not be reported as they are not considered directly related to nuclear safety. [22]

In their Master's thesis, Hankivuo discusses methods to prevent common cause failure due to electrical grid disturbances in NPPs. They describe the structure of the electrical systems in Finnish NPPs, and introduce several system level modifications that could have an effect on the common cause fault tolerance of the plant. The electrical disturbances that are discussed in the thesis are limited to lightning

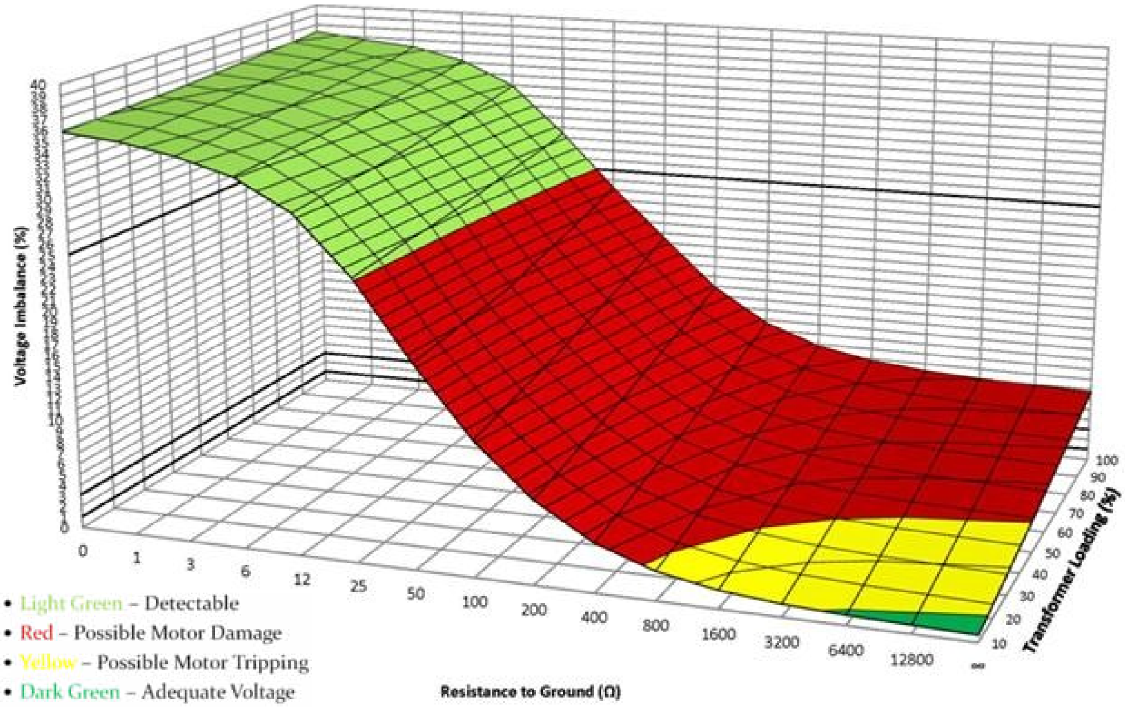

Figure 3: Voltage unbalance vs. fault impedance and transformer loading in OPC according to Khandelwal and Bowman. [21, p. 97]

strikes, short circuits, ground faults and phase interruptions. These disturbances can potentially cause overvoltages, undervoltages, overcurrents, phase unbalance as well as frequency deviations in the electrical system. [23]

Wämundson presents a survey of operational events related to NPP electrical disturbances, as well as a few possible mitigating measures against failures caused by such disturbances. Wämundson's survey consists of a review of three pieces of literature and descriptions of several relevant events at Nordic NPPs. The first reviewed article is a study by the European Clearinghouse on Operational Experience Feedback for NPPs, which reviewed approximately 600 event reports and identified a number representative events. Wämundson considers four of these relevant: [24]

- A 1990 event in Dukovany, Czechia, where a single short circuit ended up tripping all four units at the site
- A 2006 event in Chashma, Pakistan, where the plant lost external power and failed to transfer to house load operation, and one of the two emergency diesel generators (EDG) partially failed
- A 2001 event in Maanshan, Taiwan, where a malfunction in medium voltage equipment caused a fire that disabled all safety trains and caused a station blackout (SBO) for several hours
- A 1993 event in Kola, Russia, where grid instability, design deficiencies and procedural problems caused EDG failure.

The other two articles are reports by the US Nuclear Regulatory Commission (NRC), which assess the effects of external grid faults on NPPs. Wämundson highlights several conclusions and recommendation from these reports, which include:

- Many plant trips and loss of offsite power (LOOP) events could be avoided if existing protection systems worked as intended
- Reducing backup protection delays may reduce or mitigate the effects of some electrical transients
- Improving the reliability of protection systems and switchyards in general would reduce the frequency of grid events
- Several specific noteworthy occurrences, including a case where a grid transient affected the scram capability of the reactor and a case where overfrequency after a load rejection caused dangerously high coolant flow rates.

Nordic events highlighted by Wämundson include the 2006 Forsmark event, the 2008 Olkiluoto event, several events where lightning strikes or short circuits in the grid caused tripping of power electronics components, two OPC events, as well as several cases where grid protection systems operated incorrectly. [24]

Wämundson notes that extensive electrical system studies have been performed at Nordic NPPs after the 2006 Forsmark incident. These studies include assessing possible scenarios and then simulating them to estimate the behaviour of plant systems. However, they note that these studies have not been able to prevent all electrical events with possible safety implications. Therefore, the paper presents four actions for mitigating such events. The first recommendation is OPC detection, while the second one is circuit breaker duplication (series connection). The other two actions are higher level concepts: duplicated analyses, where technical analyses are performed independently by two parties for quality control purposes, as opposed to current practice where they are performed by a single person or inherit data from previous analyses; as well as the concept of “withstand or isolate”, where the boundaries for acceptable conditions for a piece of equipment are clearly defined and the equipment is reliably isolated from the grid outside these boundaries. The latter appears very similar to the “acceptability and detectability” concept presented by Khandelwal and Bowman in their ROBELSYS paper. [24]

Brück et al. briefly describe German efforts to analyse common cause electrical failures using PSA methods. They note that this work was originally inspired by several OPC incidents, but that other electrical failures were also included. They list 10 OPC events as well as the 2006 Forsmark event, and a 2011 event at Grohnde power plant where four inverters in separate redundant trains failed due to a single 660 V breaker failure. The work included the review of a large number of event reports from German and American plants, and during the review, 29 relevant events were identified. Out of these events, three scenarios have been developed so far; it is not stated what these are or whether more scenarios will be developed in the future. [25]

The scenarios were simulated using the Neplan software. A generic German plant electrical system model was developed for this purpose, and simulations such as load flow calculations, short circuit calculations, harmonic analyses and dynamic simulations were performed. The authors claim that this model is suitable for estimating the impact of different scenarios on the plant electrical systems. Finally, they note that integrating common cause electrical failure scenarios into existing

PSA models requires significant modifications and additions. In particular, they estimate that finding appropriate reliability parameters such as failure rates for the affected equipment would require significant work. As a first step, the authors have assessed the rate of single OPC in the grid connection to be similar to the rate of small LOCA. [25]

2.6 Regulatory requirements

Nuclear safety regulation places certain requirements on electrical systems in NPPs. In Finland, these requirements are detailed in YVL guides B.1 [26] and E.7 [27] published by the Radiation and Nuclear Safety Authority (STUK). YVL B.1 contains a section describing basic design principles of NPP electrical systems, whereas YVL E.7 is concerned with the qualification and documentation of electrical components. Some of the relevant requirements presented in YVL B.1 include:

- Equipment necessary for house load operation is required (5402).
- Both the external and internal electrical power sources must be capable of activating all safety functions (5403).
- Electrical failures must be prevented from spreading from one redundant system to another (5407).
- Voltage and frequency fluctuations caused by internal systems and the external grid must be analysed, and they must not affect safety systems (5408, 5409).
- Two independent connections to the external grid are required (5417).
- The plant must support automatic switchovers between different power sources, and operators must also be able to activate them manually (5422, 5424).
- Electrical systems must be equipped with protective devices that selectively trip faulted components (5470).
- Such protective devices must be tested regularly (5476).

From these requirements, it can be seen that Finnish nuclear regulation does not place any requirements regarding specific electrical faults. Instead, all potential faults should be considered as part of the overall reliability of the electrical system.

2.7 Grid codes

Transmission system operators (TSO) place certain requirements on power plants connected to the electrical system. Such requirements are detailed in grid codes and related specifications. The purpose of these requirements is to ensure that power plants can reliably withstand the voltage and frequency conditions present in the system, as well as to prevent them from causing disturbances in the grid. For example, the Finnish grid code specifies a frequency range of 47.5 Hz to 51.5 Hz [28], which the system is not expected to deviate from even during significant disturbances. Similarly, the allowed voltage range in the 400 kV network in Finland is 360 kV to 420 kV [28]. However, the voltage can deviate from this range due to various fault conditions, as voltage is more of a local rather than global quantity.

One of the more specific requirements is the ability to withstand a temporary short circuit fault in the grid near the power plant. During such a fault, the voltage is reduced to 0 and no active power can flow from the power plant to the grid, until the fault is cleared by the protection. Power plants must resume normal operation after the fault is cleared to prevent the power system from collapsing due to such relatively common faults. This fault-ride-through requirement is of interest in the COSI project due to its time dynamic nature. It represents a transient which the grid companies expect to occur in the power system. As a formal requirement, power plant operators are presumably already equipped to analyse its effects on the plant systems.

The detailed voltage profile of the fault-ride-through requirement is slightly different between different grid operators. The profile can also be different depending on the type and size of the generator as well as the voltage level of the grid connection. Figures 4 and 5 display the voltage profiles for a large synchronous generator connected to the 400 kV grid in Finland and Sweden, respectively. In both systems, the voltage before the fault is 1 pu and the fault occurs at 0 s. In the Finnish system, the fault (at 0 pu voltage) is expected to last 200 ms, after which the voltage recovers linearly from 0.25 pu to 0.85 pu between 0.25 s and 1 s. Additionally, the voltage recovers to 0.9 pu at 10 s (not shown). Meanwhile, in the Swedish system, the fault is expected to last 250 ms, with a linear recovery from 0.25 pu to 0.9 pu between 0.25 s and 0.75 s. The fault time is slightly longer in the Swedish than in the Finnish profile, while the voltage recovery is slower in the Finnish profile.

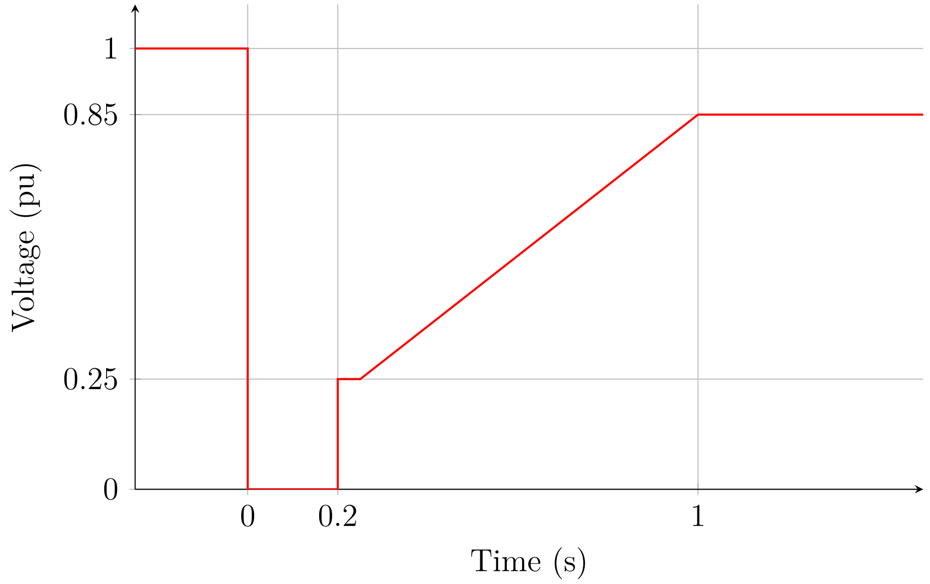

Figure 4: Fault-ride-through voltage profile in Finnish transmission grid for large generators. [28]

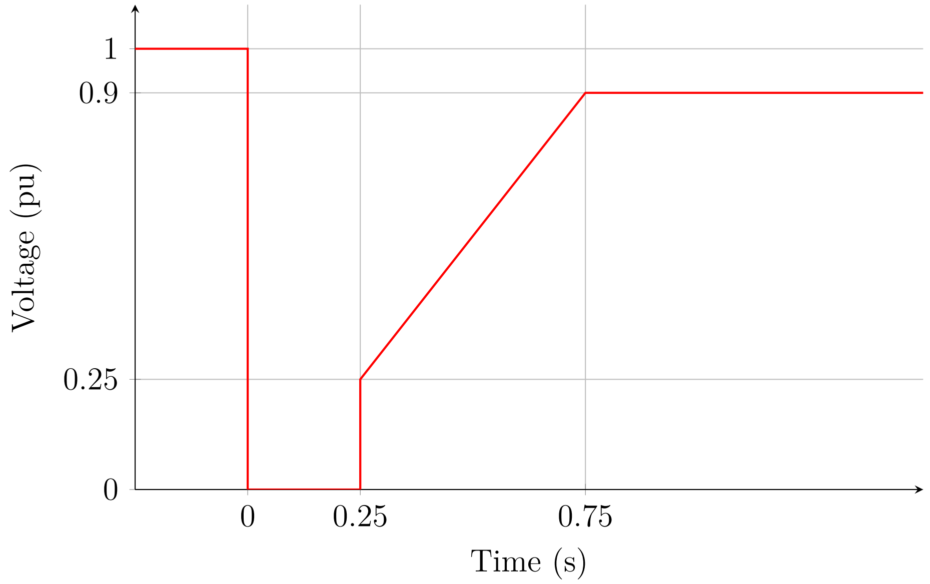

Figure 5: Fault-ride-through voltage profile in Swedish transmission grid for large generators. [29]

3 Power frequency overvoltages

3.1 Overview

An overvoltage is a condition where the voltage applied to a system or component exceeds the voltage which it was designed for. Typically, overvoltage conditions are transient in nature, lasting from nanoseconds up to minutes at most. Overvoltages are divided into transient overvoltages and power frequency overvoltages depending on the length of the condition. Transient overvoltages are typically caused by lightning strikes or switching operations, while power frequency overvoltages can originate from sources such as grid faults, resonance conditions or voltage control malfunctions. [30]

Overvoltages can cause damage to equipment, and therefore they must be prevented or limited. Some types of overvoltages can be limited using surge arresters, which become conductive at high voltages and shunt the excess energy away from sensitive equipment. However, the energy quenching capacity of surge arresters is limited, so they cannot be utilised for longer lasting overvoltages such as power frequency overvoltages. Instead, these kinds of overvoltages should be prevented with appropriate grid design and operational principles. [30]

Short circuits and ground faults are an important cause of grid transients, including overvoltages. A short circuit is a condition where two or three phases are connected to each other with a low impedance. A ground fault is a similar condition where one or two phases are connected to ground with a low impedance. Short circuits and ground faults are the most common types of faults in an electrical system, and they are typically caused by lightning, equipment failure (mechanical or dielectric), or switching error. Short circuits cause high currents to flow, and the fault must be isolated from the system quickly to avoid danger and damage to equipment. [30]

Short circuits, their clearance, and other electrical changes associated with such faults are often dimensioning factors when designing electrical systems. Therefore, analysing these situations is important to ensure the reliability of the completed system. Transients that exceed the design basis can potentially cause complicated failures, which could have safety implications in an NPP.

3.2 2006 Forsmark event

On 25 July 2006, a short circuit occurred at the offsite 400 kV substation of Forsmark units 1 and 2 in Sweden. The two-phase fault was caused by a maintenance error, where an electrical arc formed and spread when a disconnector was opened under load. At that time, unit 1 was operating at full power while unit 2 was disconnected for maintenance. The fault caused substantial undervoltage in the short circuited phases. An additional failure in the primary protection caused a delay to the clearing of the fault, and when the unit breaker finally opened, a voltage 118 % of nominal was fed into the plant systems. The cause of this overvoltage was generator overexcitation, as the excitation system compensated for the undervoltage during the prolonged fault condition. [18], [22] As a result of the overvoltage transient, the uninterruptible power supplies (UPS) in two of four redundant safety divisions tripped. The UPS systems are responsible for feeding safety critical AC loads from the battery backed DC system. It is not known why two of the UPS systems did not trip, but it is thought to be due to small differences in the electrical circuits in the divisions. The safety critical loads supplied by the UPSs include emergency cooling systems as well as instrumentation and control systems, such as measurements, indications and control room displays. Importantly, this also included rotational speed measurements required for connecting the emergency diesel generators (EDG) to their respective bus. [18], [22]

The turbines were tripped due to the fault. As the generators coasted down, their frequency dropped. However, the underfrequency protection of the generators was misconfigured, so the underfrequency protection between the auxiliary (non-safety) and diesel-backed (safety) buses tripped first. This left the safety buses disconnected from the external grid. When the safety buses lost power, the diesel generators started, but only two of the four EDGs were able to connect to their busbars as described earlier. [18], [22]

With power supply for the critical AC loads disabled from both the UPSs and the safety busbars in two divisions, many I&C devices in the plant were unable to function. Reactor pressure vessel pressure measurement failed, causing the pressure relief valve to open as a failsafe. Auxiliary feedwater systems were barely able to keep up with the loss of coolant through this valve, as half of the pumps were disabled. Finally, 22 minutes after the incident started, the operators manually reconnected the safety busbars to the non-safety busbars, restoring all plant functionality. [18], [22]

3.3 Discussion

Overvoltages are divided into two types depending on the length of the condition. Shorter overvoltages are known as transient overvoltages, and they are caused as the direct result of lightning or by many types of switching operations. Nuclear power plants are generally considered to be well protected against transient overvoltages [18], as these kinds of overvoltages can be limited using surge arresters. Some research performed in the ESSI project found that NPPs could be vulnerable to lightning overvoltages due to ground potential rise in certain cases [13]. However, lightning overvoltages are excluded from the COSI project, as they operate on very a different timescale compared to other issues considered in the project.

Longer-lasting overvoltages are known as power frequency overvoltages, as they typically occur at or near the main frequency of the power system. Typical causes of these overvoltages include ground faults, sudden loss of load, reactive power imbalances, voltage control issues and resonance conditions. A single phase ground fault causes overvoltage in the remaining phases, and the magnitude of the overvoltage depends on the grounding of the neutral points in the system. A sudden loss of load can cause overvoltages due to the sudden reduction in voltage drop or changes in reactive power balance. Excessive reactive power from unloaded power lines, capacitive loads or compensation can also cause overvoltages. Another obvious cause is failure or misconfiguration of voltage control in reactive compensation or generator excitation systems. [30]

Power frequency overvoltages cannot be quenched using surge arresters, as they carry a significant amount of energy due to their long-lasting nature. Surge arresters have a limited energy quenching capability, which is incompatible with such amounts of energy. Instead, equipment needs to be disconnected from the system by overvoltage protection when the supply voltage reaches too high a level. However, it may not be trivial to determine the direction from which the overvoltage is coming, particularly if generators are involved.

In the Finnish electrical system, the grid code specifies a maximum operating voltage of 420 kV for the 400 kV network [28]. Outside this limit, power plants are allowed to disconnect from the grid. Additionally, plants are expected to tolerate a 10 % overvoltage (440 kV) for 60 minutes [28]. In addition to these long term voltage levels defined in the grid code, single phase ground faults are expected to cause shorter overvoltages of up to 140 % of nominal in the effectively grounded Finnish 400 kV network [30].

Many studies into overvoltage events and other electrical transients appear to be inspired by the 2006 Forsmark event (described in Section 3.2) as well as a 2008 event at Olkiluoto. At Olkiluoto unit 1, the generator excitation system failed, erroneously providing full magnetising current, which resulted in increasing generator voltage. The overvoltage protection was designed to protect the plant from grid overvoltages, so it disconnected the unit breaker, leaving the generator connected to the internal loads at the plant. This resulted in a voltage transient of 150 % of nominal, which tripped all recirculation pumps simultaneously, but did not cause any permanent damage. [18]

Electrical transients appear to be a somewhat recognised risk factor in NPP systems. According to literature, electrical transients have only been analysed superficially during the original design of many plants. The same may be true for later modifications to the plants. There are no specific standards or regulatory requirements that address how electrical transients should be analysed. As such, the 2006 Forsmark event served as a reminder that a simple electrical transient, such as an overvoltage event, can potentially cause a a complicated chain of failures in a system that is not prepared to handle such transients.

Several papers present a concept known as “withstand or isolate”. According to this concept, plant systems are designed to tolerate and function normally under specified conditions, such as overvoltage. Outside these conditions, electrical protection systems will reliably isolate the fault or disconnect the equipment. The concept involves in-depth analysis to ensure that the boundary between “withstand” and “isolate” is well defined, that every device can withstand the required conditions, and that the protection outside the conditions is reliable.

Many papers found in the literature call for standardised tests for electrical transients, in the form of voltage and frequency profiles. This concept is already widely used in other related industries, such as grid codes and lightning impulse testing. Standardised profiles would ensure that every plant is consistently aware of the types of transients that can occur in the electrical system. However, the obvious drawback is that analysis could be inadvertently limited to these standardised cases, neglecting the possibility of unforeseen occurrences.

Existing electrical simulation studies in NPPs appear to be mainly focussed on normal plant functionality, such as load flow, motor startup and short circuit analyses. However, some efforts have already been made to analyse various grid fault scenarios systematically. These efforts include the work on disturbance profiles at Oskarshamn, described in the ROBELSYS and DIDELSYS reports, as well as the work by Brück et al. on the use of PSA methods for analysis of electrical faults [25].

None of the analyses found in the literature have simulated the progression of overvoltages and other electrical transients as a function of time. As transients and their effects are fundamentally time based, such simulations could be seen as a natural way to analyse them. Furthermore, all existing analyses seem to be limited to electrical effects, even though the effects on the process systems of an NPP are ultimately the most interesting from a safety perspective. These limitations are inherent to static analysis even if a concept such as “withstand or isolate” is applied. As various past incidents show, the failure modes and effects can be complicated and difficult to foresee. Therefore, detailed time domain simulations could be beneficial for understanding the effects of various electrical transients on plant systems.

4 Open phase conditions

4.1 Overview

An open phase condition (OPC) occurs when one or two of the three phases are disconnected due to partial circuit breaker malfunction, conductor break or other mechanical failure. This causes a very unbalanced situation downstream of the fault, but typical protection may not be able to detect the fault and isolate it. This is particularly true in low load cases. The missing phase may be regenerated in a transformer to some degree, depending on its phase configuration, neutral point treatment and core construction. This exacerbates the difficulty of detecting the fault even further. [30], [31]

The main effect of an imbalance condition such as OPC is decreased torque and greatly increased heating in synchronous and asynchronous rotating machines. The main generator in a power plant is typically protected against asymmetric conditions and will be disconnected in case an OPC occurs. However, in a prolonged imbalance situation, such as an undetected OPC during a plant outage, induction motors may stall or be disconnected or damaged due to excess heating. [31]

What makes upstream OPCs particularly harmful is their ability to cause simultaneous failures in all redundant trains that are connected to the same point in the grid. Indeed, OPCs have resulted in difficult to diagnose common cause failures in nuclear power plant safety systems, and OPCs are recognised as having an adverse impact on plant safety. However, for the same reason, OPCs in internal plant systems are not considered particularly problematic, as the impact of such a fault is limited to a single redundant train. [31]

4.2 Symmetrical components

Generally, three phase systems are analysed using single phase equivalent circuits, and the quantities of the other two phases are obtained simply by phase shifting those of the first phase by 120° and 240°. This works for balanced circuits, where voltages and currents are symmetrical. However, this is not the case in asymmetric situations, such as ground faults and open phase conditions. In these cases, the phase voltages and currents can have different magnitudes and any phase angles. Analysing all three phases separately would triple the number of equations required to solve the system, and would therefore be complicated. [30]

However, it turns out that an arbitrary three phase quantity can be expressed using three symmetrical components. These components are linearly independent wherever the network itself is balanced, meaning that current flowing in one system causes a voltage drop in only that system and vice versa. Therefore, each network can be analysed separately as a single phase equivalent and the networks connected to each other only at the unbalanced fault point. This also means that this method is particularly effective only when there is a single imbalance in the system. [32], [30]

As the components are by definition always symmetrical, only one phase quantity needs to be stated from each component. The components are referred to as the positive, negative and zero sequence component ($\underline{U}_1$, $\underline{U}_2$, $\underline{U}_0$). In each component, the phasors rotate in the same direction at the same frequency. The positive sequence system is a normal balanced three phase system with phase sequence RST, whereas the negative sequence is similar but with the opposite phase sequence (RTS). In the zero sequence system, each phase has the same magnitude and angle, that is, the zero sequence component represents a common mode signal. [30]

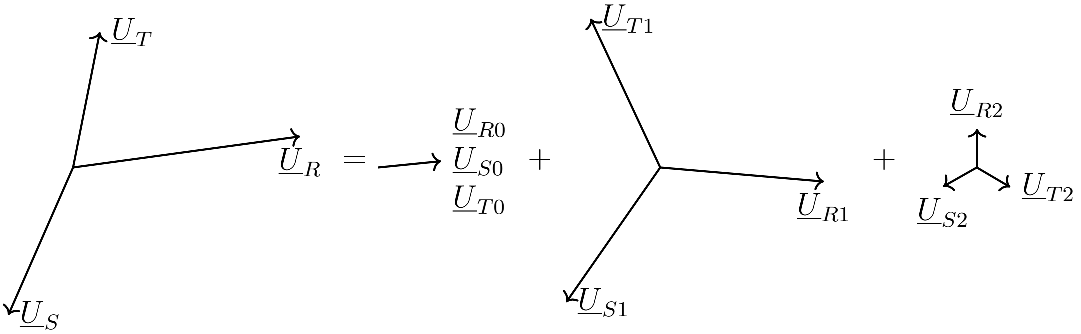

Figure 6: Asymmetric three phase voltage and its symmetrical components.

Figure 6 represents an asymmetric three phase voltage and its constituent symmetrical components. The three phase voltages of the positive sequence component can be expressed using the phase rotation operator $\underline{a} = e^{j120°}$ as

$$\begin{aligned} \underline{U}_{R1} &= \underline{U}_1 \\ \underline{U}_{S1} &= \underline{a}^2 \underline{U}_1 \\ \underline{U}_{T1} &= \underline{a} \underline{U}_1 \end{aligned} \tag{1}$$

Similarly for the negative sequence voltages:

$$\begin{aligned} \underline{U}_{R2} &= \underline{U}_2 \\ \underline{U}_{S2} &= \underline{a} \underline{U}_2 \\ \underline{U}_{T2} &= \underline{a}^2 \underline{U}_2 \end{aligned} \tag{2}$$

Finally, the zero sequence voltages are all equal as already discussed:

$$\underline{U}_{R0} = \underline{U}_{S0} = \underline{U}_{T0} = \underline{U}_0 \tag{3}$$

The asymmetric voltages can be constructed simply by summing the symmetrical components for each phase:

$$\begin{aligned} \underline{U}_R &= \underline{U}_{R0} + \underline{U}_{R1} + \underline{U}_{R2} \\ \underline{U}_S &= \underline{U}_{S0} + \underline{U}_{S1} + \underline{U}_{S2} \\ \underline{U}_T &= \underline{U}_{T0} + \underline{U}_{T1} + \underline{U}_{T2} \end{aligned} \tag{4}$$

Equations 1 to 4 can be combined and presented in matrix form:

$$\begin{bmatrix} \underline{U}_R \\ \underline{U}_S \\ \underline{U}_T \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a}^2 & \underline{a} \\ 1 & \underline{a} & \underline{a}^2 \end{bmatrix} \begin{bmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} \tag{5}$$

The corresponding symmetrical components can be calculated from the asymmetric phase voltages with the inverse matrix:

$$\begin{bmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{bmatrix} \begin{bmatrix} \underline{U}_R \\ \underline{U}_S \\ \underline{U}_T \end{bmatrix} \tag{6}$$

Equations 1 to 6 also apply to currents as well as voltages as presented here. [30]

Because the symmetrical components are independent from each other, and because generators only produce positive sequence voltage,

$$\begin{bmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \underline{E}_1 \\ 0 \end{bmatrix} - \begin{bmatrix} \underline{Z}_0 & 0 & 0 \\ 0 & \underline{Z}_1 & 0 \\ 0 & 0 & \underline{Z}_2 \end{bmatrix} \begin{bmatrix} \underline{I}_0 \\ \underline{I}_1 \\ \underline{I}_2 \end{bmatrix} \tag{7}$$

Each of these impedances can be determined separately for the electrical network in question. As the component networks are to be connected together at the asymmetric fault point, the impedances represent equivalent impedances seen from the fault point. Each type of device in the network affects the impedances in a different way. The positive sequence impedance is simply the regular short circuit impedance of the line or device. The negative sequence impedance is the same as the positive sequence impedance if the impedance does not depend on the phase sequence. This is true in most cases, but notably not for rotating machines. However, the zero sequence impedance is typically quite different from the previous two. In particular, a finite zero sequence impedance requires that a current path exists from the neutral point to ground. Any impedances between the neutral point and ground are multiplied by 3 in a single phase equivalent circuit, because all three zero sequence phase currents pass through the same impedance. [30], [32]

Transformer winding connections have a significant effect on the zero sequence impedance. In short, grounded wye windings can pass zero sequence currents, while delta and ungrounded wye windings cannot pass them, although a delta winding acts as a short circuit for zero sequence currents that have entered the transformer through a grounded wye. In addition to winding connections, the magnetic circuit of a transformer, i.e., the construction of the core, has an important effect on the zero sequence impedance. Shell type cores and five leg cores provide a low reluctance path for the zero sequence field, while three leg cores do not, resulting in a higher zero sequence impedance in the latter. [30]

Whether loads are considered when analysing a system depends on the type of situation being modelled. Typically, shunt faults such as short circuits and ground faults cause such high fault currents that the load currents can be ignored without causing any significant error, simplifying the analysis. On the other hand, when modelling unbalanced loads, open phase conditions or similar situations, the loads must naturally be considered as they contribute most of the current. [32]

When the symmetrical component impedances have been determined, the networks are connected to each other at the fault point. The type of situation being modelled determines how the networks connect together. In some cases, such as a single phase open circuit condition, the connection is obvious from the definitions of the condition. In any case, these connections are catalogued in textbooks such as [32] (p. 90–91, 158–159). In a single OPC (Figure 7), $\underline{I}_R = 0$ and $\underline{U}_S = \underline{U}_T = 0$. If we insert these values into Equation 6, we notice that $\underline{U}_0 = \underline{U}_1 = \underline{U}_2$; i.e., the networks are connected in parallel (Figure 8).

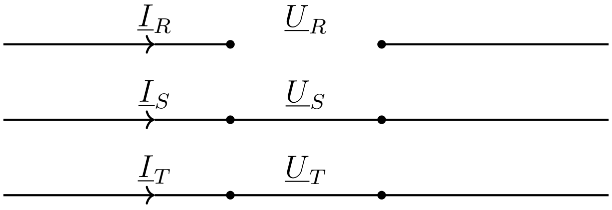

Figure 7: Single phase open circuit in phase R.

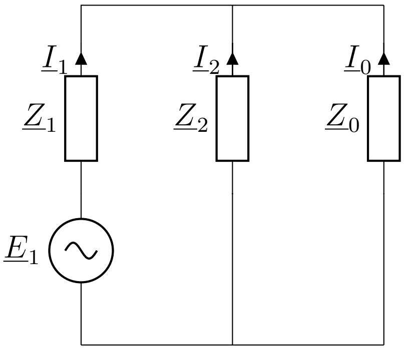

Figure 8: Component networks connected at the fault point in single OPC.

4.3 Literature

In addition to the reports published from ESSI, several pieces of literature that specifically consider OPC in NPPs were identified. An IAEA report on the subject [31] considers different conditions in which OPC can occur, discusses the effects it has on different types of equipment, and describes how plants could evaluate their susceptibility. The report also lists 14 OPC events that have occurred at NPPs along with short a description of each. Investigation into OPCs was particularly inspired by two separate events at Byron in 2012 as well as an event at Forsmark in 2013.

The report considers induction motors and power electronics devices the most vulnerable to OPCs, with transformers not considered vulnerable and main generators already effectively protected against OPC. The report also considers spurious actuation of protective relays, such as overcurrent relays, to be a type of equipment vulnerability. When it comes to analysis of OPCs, the report states that a systematic evaluation or simulation study is necessary. Some calculation and simulation models have been tested to verify their accuracy. The withstand capability of equipment should be analysed, and protective measures implemented for cases where the imbalance exceeds what the equipment can withstand. This idea resembles the concept of "withstand or isolate" discussed earlier in the context of electrical failures in general. [31]

Christensson and Lingärde analysed the OPC characteristics of transformers in a laboratory setting in their Master's thesis. They measured secondary side voltage and current imbalances with different core constructions, phase connections and load conditions during single and dual OPCs. The results were in agreement with those obtained using analytical methods. They also compared the results with earlier simulation studies of Oskarshamn NPP main transformers, and found similarities despite the massive size difference between the transformers considered in the simulations and their laboratory study. [33]

Myrttinen simulated OPC events at Loviisa NPP in their Master's thesis. They simulated single and double OPC in both grid connections under several different plant states and load levels using a Simulink model. They found that the OPC had an effect on the loadability of motors in some cases, and that the OPC could be detected using existing protection relays in some cases and not in others. The results were found to be very similar to other studies conducted at Loviisa and at other plants. [34]

4.4 2012 Byron event

On 30 January 2012, Byron unit 2 in the United States experienced a reactor trip due to undervoltage on a medium voltage bus. The electrical system at Byron is configured such that in normal operation, half of these redundant buses are supplied from a unit auxiliary transformer, while the other half is supplied from a station auxiliary transformer. The cause of this undervoltage condition was a broken insulator on the high voltage side of the station auxiliary transformer. This resulted in an open phase condition without ground contact, and the fault was not detected or cleared by any protection. [31]

The reactor trip initiated a transfer of all unit auxiliary transformer loads to the station auxiliary transformer. As a result, all medium voltage buses were now fed from the faulted electrical source. This caused further imbalance in the supply voltage, and all reactor coolant pumps tripped due to overcurrent. The OPC was still not detected, and the faulted line continued to supply safety related loads, some of which were tripped by various overload protections. Finally, 8 minutes after the event started, the operators manually disconnected the faulty line, and the EDGs started, restoring all plant functionality. [31]

Less than a month later, on 28 February 2012, Byron unit 1 also experienced a similar OPC on the high voltage side of the station auxiliary transformer. However, this time, the broken conductor caused a short circuit, which was correctly isolated by the protection. Plant loads were automatically transferred to the unit auxiliary transformer as designed. [31]

4.5 Discussion

OPCs are typically caused by mechanical failures, such as conductor breaks or failed breaker poles. Individual breakers poles can fail to open or close when commanded, causing a single or dual OPC depending on the situation. The level of phase imbalance experienced downstream of the OPC depends significantly on the construction and phase connection of any transformers involved. The downstream load level and type of loads also affect the phase imbalance. As a consequence, the state of the plant (operation, outage, startup, etc.) during the OPC affects the presentation and impact of the fault. [31]

An unbalanced supply voltage affects the behaviour of connected loads, with induction motors and power electronics devices affected the most. Induction motors are affected by the negative sequence component of the supply voltage, which produces a torque opposing the normal rotation of the machine. Typically, the negative sequence impedance of an induction motor is significantly lower than the positive sequence impedance, and therefore even a small supply imbalance produces large currents. The opposing torque reduces the amount of normal torque available to turn the load, which may result in reduced rotational speed or even stalling. The negative sequence current and the increased positive sequence current cause significantly increased heating in the machine. The 100 Hz rotor currents induced by the negative sequence component also cause vibrations. [31]

If the imbalance situation is prolonged, the increased heating may damage the motor and render it inoperable. This is particularly true if the motor is stalled. Many motors are equipped with protections that may trip during an imbalance condition. These protections can measure values such as undervoltage, overcurrent, overload, temperature or vibration. If a motor or other device trips due to any of these protections, it will not be able to function. This is of particular concern if multiple devices in different redundant trains are disabled due to a single OPC upstream. Protection trips are also the reason power electronics devices are vulnerable to OPCs.

OPCs can have an effect on the plant even if motors are not damaged. The decreased torque can cause a reduction in the rotational speed of the motor, or even a stall. The reduced speed has an effect that depends on the purpose of the motor. If the motor is turning a pump, the fluid flow rate would decrease, which would affect the process system accordingly.

Furthermore, a change in a process system would be reflected back to the electrical system, as the torque and power of the load are defined by the process. For example, reduced fluid flow could cause a reduction in the torque of a motor, resulting in decreased current and increased voltage. In another hypothetical situation, tripping of a load could cause backup systems to activate, increasing the total load on the electrical system.

According to literature, OPC appears to be a fairly well recognised issue affecting NPP electrical systems. Most NPP designs did not originally consider OPC, and consequently many plants were vulnerable to common cause equipment failure due to open phases. However, since the publication of several OPC incidents in 2012–2013, awareness of the issue has grown among regulators and plant operators. It appears that many plants have performed some kind of analysis to determine whether their systems are vulnerable, and implemented relevant corrective actions.

Common methods found in literature for analysing OPC include analytical calculations using symmetrical components and time domain simulations using three-phase models. Laboratory measurements have also been used to validate the analytical models with real life transformers and induction machines. Analysis seems to be limited to the electrical system, with effects on electrical components and electrical protection as well as the process system analysed separately from the actual simulation. This kind of approach would be unable to consider any feedback loops or other effects arising from outside the electrical system. Existing analyses are also often most interested in the steady state behaviour of the system after an OPC, neglecting any transient behaviour.

Many OPC simulation studies, including [34] and several other studies referenced in that work, utilise an approximated model where several motors are combined into a single large unit. This is a useful method to simplify the model without compromising the accuracy of the electrical simulation. However, this approach limits the simulation to electrical values and does not allow interactions with other systems.

A common theme found in vulnerability analyses is the “withstand or isolate” concept. It can be applied to many types of electrical disturbances, including OPCs. According to this concept, plant electrical systems are designed to be capable of operating up to a certain level of imbalance, and any faults that cause an imbalance higher than this are reliably detected and disconnected. A focus on detection of OPCs can therefore be seen in literature, somewhat at the cost of analysing the effects they have on plant systems. The reasoning behind this kind of focus could be that plant systems do not need to tolerate imbalance conditions if OPCs are reliably detected.

Ultimately, the potential impact of an open phase condition depends on how long the situation lasts before being cleared (either manually or automatically), compared to the time it takes for the effects to occur. For example, increased temperatures due to overload conditions often take minutes or hours to develop, while feedback from process systems could occur at any speed. As the effects of OPCs in NPPs are fundamentally time based phenomena, time domain simulation could be seen as a natural way to analyse them. Time domain simulation is also an ideal method to analyse the transient behaviour of a system.

5 Subsynchronous oscillations

5.1 Overview

Dynamic analysis of power systems often assumes turbine generators to consist of a single mass. This kind of representation is adequate for many types of analyses. However, in reality, a turbine generator rotor has a complex mechanical structure where several different turbines as well as the generator and exciter are interconnected with a long shaft. The structure of such a rotor is illustrated in Figure 9. When the rotor is perturbed, these different sections will oscillate against each other torsionally due to the finite stiffness of the shaft. The damping level of such torsional oscillations is typically very low. Therefore, if the electrical system were to excite these modes of oscillation, the amplitude of the oscillations could grow unbounded and cause serious damage to the turbine generator. Typically, only modes with frequencies below the synchronous frequency (subsynchronous) interact with the electrical system. [35]

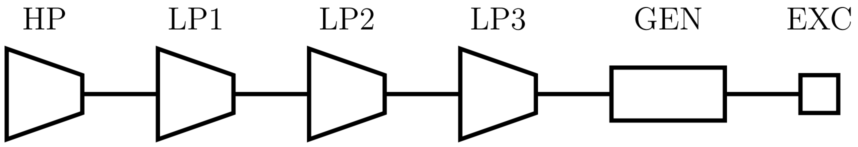

Figure 9: Schematic diagram of a rotor with a high pressure turbine, three low pressure turbines, a generator and an exciter.

Subsynchronous oscillations (SSO) are traditionally divided into two types of interactions depending on the types of devices participating in the interaction. Table 1 lists the different types of oscillations. Interactions between a synchronous generator and active devices in the grid, such as control systems of HVDC converters, static var compensators or the power plant itself, are known as subsynchronous torsional interactions (SSTI) or device dependent subsynchronous oscillations (DDSO). On the other hand, interactions between a synchronous generator and series compensated power lines are known as subsynchronous resonance (SSR). Here, the generator interacts with the LC circuit formed by the inductance of the line and the generator, and the capacitance of the series compensation. Three different types of SSR are recognised. [36], [37]

The first type of SSR is the induction generator effect (SSR-IGE). A synchronous generator behaves like an induction generator at subsynchronous frequencies, such as the natural frequency $f_n = 1/(2\pi\sqrt{LC})$ of a series compensated network. At these frequencies, the generator acts as a negative resistance. If the negative generator resistance exceeds the network resistance, self-excitation will result and the RLC circuit will oscillate uncontrollably. Note that the induction generator effect is purely an electrical phenomenon and does not depend on the mechanical characteristics of the rotor, unlike other types of SSR. [35], [36]

The second type is torsional interaction (SSR-TI, not to be confused with SSTI). It occurs when the complement of the natural frequency of the electrical system is close to one of the torsional frequencies of the turbine generator. When a current with subsynchronous frequency f_n is applied to the generator, the rotor will experience torques with frequencies $f_1 = f_0 - f_n$ and $f_2 = f_0 + f_n$, where f_0 is the synchronous frequency. If the subsynchronous component f_1 is close to a torsional frequency, the electrical and mechanical systems will be tightly coupled with each other and negatively damped resonance may occur. [35], [38]

The third type is known as torque amplification (SSR-TA). Like torsional interaction, this also occurs when the complement of the electrical system's natural frequency is close to a torsional frequency. Disturbances in the electrical grid induce electrical oscillations at the natural frequency. The interaction of these oscillations with the torsional modes of the rotor causes transient torques that are much higher than would occur in a non-series-compensated network. [36]

A more recently discovered type of SSO is known as subsynchronous control interaction (SSCI). In the two traditional types of subsynchronous oscillations, SSTI and SSR, the oscillations are related to interactions between a synchronous generator and other components in the electrical grid. In contrast, SSCI is related to interactions between the control system of a wind power plant and other grid components (typically series compensation). [37]

Table 1: Types of subsynchronous oscillations.

SSTI	**SSR**	**SSCI**
SSTI-HVDC	SSR-IGE	
SSTI-SVC	SSR-TI	
etc.	SSR-TA	

Subsynchronous oscillations should be distinguished from oscillations where the entire turbine generator oscillates against the power system as a rigid body, or a group of generators oscillates against another. The latter typically occur at frequencies from below 1 Hz to several Hz, while the former occur at higher frequencies. The latter are typically considered in system stability studies, and only depend mechanically on the synchronising torque of the generator and the total inertia of the rotor. On the other hand, the former involve the full interaction of both the electrical and mechanical systems. [35]

5.2 Literature

The literature review identified an application of co-simulation to analysis of SSR. Xie et al. were inspired by recent SSR events in China and India to analyse the effects of SSR on the turbine generator shaft in detail. They were particularly interested in mechanical effects such as fatigue loss-of-life. Therefore, they needed detailed data about the torques and stresses inside the shaft material. Out of all methods used to analyse SSR, torque information is provided only by time domain simulations. However, typical SSR simulations use a lumped mass model (LMM) of the rotor, which is a simplified mechanical representation where rigid masses are connected to each other by springs. Instead, the authors preferred a more detailed continuous mass model (CMM). Unfortunately, most electrical transient simulation programs are not capable of such detailed mechanical simulations, and conversely, mechanical simulation software is not suitable for electrical simulation. [40]

To combine electric transient analysis with CMM analysis of the shaft, the authors used a co-simulation method, where two simulation programs are run simultaneously and exchange data with each other. They compared the results from both CMM and LMM simulations as well as coupled and decoupled CMM simulation in a case study. The results of these different simulations were similar, but the coupled CMM simulation was the most accurate. They found that a LMM simulation is applicable to some types of SSR analyses, but CMM provides the most accurate results as well as details that are required for fatigue loss-of-life analysis. [40]

5.3 1970 Mohave event

Subsynchronous resonance has been a known phenomenon since the 1930s [36]. However, until the 1970s, it was not thought to be a practical concern in real power plants or transmission systems. The importance of SSR was first recognised at the Mohave coal power plant in the United States. In 1970, when the plant was radially connected to a series-compensated transmission line, turbine generator shaft damage occurred. The cause of the failure was not recognised, and the plant returned to service after several months of repairs. However, another identical failure occurred in 1971. [41]

During the SSR events, the operators experienced flickering lights, floor vibrations and excessive field current alarms, which continued for minutes until the operators shut down the plant. Inspections of the shafts after the failures revealed damaged electrical insulation and resultant arcing in the slip ring section of the shaft. The damage was caused by excessive heating of the shaft material due to mechanical stresses from the vibration. After the incidents at Mohave, significant effort was put into research and analysis of the SSR phenomenon. [41]

5.4 Discussion

Subsynchronous oscillations can be divided into three types depending on the devices participating in the oscillation: SSTI, SSR and SSCI. In SSR, the oscillation occurs between a synchronous generator and a series compensated power line, while in SSTI the oscillation occurs between a synchronous generator and an actively controlled device in the power grid. In the more recently discovered SSCI, an actively controlled generator (such as a wind turbine) oscillates against a series compensated power line. No mechanisms or occurrences were identified where a synchronous generator would interact with another power plant, such as a wind turbine.

SSO places significant electrical and mechanical stresses on the system. If turbine generator torsional modes are involved in the oscillation, the excessive torques will typically cause shaft damage or failure in a short period of time due to fatigue. Shaft failure often requires lengthy and expensive repairs, and if the shaft were to fail explosively, missiles could hypothetically damage safety critical components in an NPP. However, SSO does not appear to have been analysed from a nuclear safety perspective before.

SSR was first recognised as a problem in the 1970s, and since then, significant research has been put into analysing the phenomenon. The causes and effects as well as the solutions to the problem appear to be well understood. In Finland, analysis of subsynchronous oscillations in general started in the 1980s, when the Fenno-Skan HVDC link was being implemented near the Olkiluoto generators [37]. Since then, such investigations have been part of routine analyses when implementing new HVDC interconnections, series compensation or large generators. The Finnish grid code requires new large generators to investigate certain special topics, including SSO, if deemed necessary by the TSO [28].

Subsynchronous oscillations can be analysed using several methods. Typical tools include frequency scanning, eigenvalue analysis and time domain simulation. The frequency scan technique determines the equivalent network impedance as a function of frequency, and gives indication about the natural frequencies of the system. It is particularly useful as a preliminary screening tool. The eigenvalue technique is based on mathematical analysis of the linearised differential equations describing the system, and can be used to examine the effects of different system configurations on SSO. Time domain analysis allows very detailed simulations, including analysis of nonlinear effects. [35], [36]

Traditionally, time domain simulations were not considered ideal for analysis of large systems due to performance issues, and because they do not provide as much useful information about the problem, such as the root cause of the SSR or how to mitigate it [35], [36], [39]. However, time domain simulation is the only type of analysis that can be applied to all types of subsynchronous oscillations, and it also provides the most details out of all analyses [37]. The performance concerns of simulations are also diminished by the increasing computational power of computers [37].

6 Conclusion

Electrical systems form the backbone of a nuclear power plant, performing tasks such as generating and transmitting electrical power, distributing power to process and control systems, and operating safety systems. Safety systems are responsible for various actions that help to prevent damage to the nuclear fuel and release of radioactive material from the plant. As such, it is important that these systems function correctly in all circumstances. The same is also true for any electrical systems which the safety features depend upon.

Safety critical systems are built with various redundancies to prevent failure of the whole system due to a single fault. Failures of several redundant parts due to a single reason, also known as common cause failures, are particularly harmful from a safety perspective. Electrical systems are vulnerable to common cause failures due to their interconnected nature, where all systems are connected together at the high voltage level. In particular, electrical events originating in the grid can have consequences in plant systems. Several real world incidents have demonstrated such vulnerabilities in operating plants.

The COSI research project aims to develop a co-simulation platform to analyse the effects of various phenomena in the electrical system on NPP process systems. This thesis reviews relevant literature and describes three conditions in detail. Several published reports and articles analyse electrical incidents in NPPs. Specific topics include classification of incident reports, evaluation of methodologies used to analyse safety systems, descriptions of safety system design principles, and reports of specific simulation studies.

An overvoltage is a condition where the voltage applied to a component exceeds what it is designed for. Overvoltages are classified into two types depending on the length of the condition. Shorter events are known as transient overvoltages while longer events are power frequency overvoltages. Transient overvoltages can be quenched using surge arresters due to their limited energy content. Therefore, NPPs are generally considered to be well protected against transient overvoltages. However, the same is not true for power frequency overvoltages. Instead, equipment needs to be disconnected from the supply if the voltage is too high.

Common causes of power frequency overvoltages are ground faults, reactive power imbalances and voltage control issues. In the Forsmark event in 2006, the generator voltage controller compensated for low voltage during a prolonged short circuit condition, and caused an overvoltage when the fault was disconnected. This event prompted increased research effort into electrical transients in NPPs.

According to literature, electrical transients may not have been adequately considered in the original design or later modifications of plants. The DIDELSYS report in particular calls for more detailed analyses using simulation methods. Many electrical simulation studies described in the literature focus on basic analyses, such as load flow, motor startup and short circuit analyses. While useful, these simulations do not assess vulnerabilities to electrical transients.

A limited number of reports were found that describe electrical transient simulation studies. Several ROBELSYS papers [20], [21] discuss simulations at the Swedish

Forsmark and Oskarshamn plants, while Brück et al. [25] describe German efforts. These studies seem to be a good starting point when considering what kinds of voltage and frequency disturbances plants are expected to encounter. However, no existing electrical simulation studies appear to consider the dynamics of other plant systems during disturbances. This is true even though other systems have played a crucial role in many incidents that were initiated by electrical transients.

An open phase condition (OPC) occurs when one or two of the three phases are disconnected. Typical reasons are mechanical failures of conductors or breakers. An OPC causes significant phase imbalance downstream of the fault, and the level of imbalance is strongly affected by any downstream transformers and different load types. In particular, transformer phase configuration, neutral point treatment and core construction affect the magnitude of the imbalance.

An imbalanced supply voltage can affect equipment in several different ways. Induction motors and power electronics devices are considered the most vulnerable to OPC. In a motor, OPC causes a reduction in available torque as well as significantly increased heating. The torque reduction can cause a reduced rotational speed or even a stall depending on the mechanical load of the motor. Overloading or overheating can cause various protections to trip the affected equipment, rendering it unavailable. In the worst case, equipment may even be damaged.

OPC can be difficult to detect using typical protection relays, including undervoltage protection, because downstream transformers and loads can regenerate the missing phases to varying extent. This is particularly true in low load cases, such as during a plant outage. In many OPC incidents, the condition went unnoticed for some time, causing individual pieces of equipment to stop functioning due to reduced torque, overload protection or damage. Due to publication of events like this, more effort has been put into analysing the phenomenon and its effects on NPPs.

Many OPC analyses found in literature focus on analysing or simulating the electrical behaviour of a single component or the entire electrical system of a plant. Typical components analysed are transformers and induction motors. Theoretical calculations, computer simulations and laboratory measurements have been found to agree reasonably well. However, analyses of entire electrical systems appear to be limited with regard to three aspects. First, most simulations use very simple models of the loads, where small loads are aggregated into larger units and all loads are modelled as constant or using a simple mathematical relationship. Second, the simulations only consider electrical effects, ignoring any potential dynamics or feedback from electrical protection or process systems. Finally, even time domain simulation studies appear to be mostly interested in steady state behaviour rather than transient effects. In OPC analysis, time dynamic effects are important, because they key question is whether motors trip, overheat or keep running until the fault is cleared.

Subsynchronous oscillations (SSO) are several related conditions where components in the electrical system interact in an oscillatory manner. They are divided into two traditional types and one more recently discovered type depending on which devices participate in the interaction. In SSR, the oscillation occurs between a synchronous generator and a series compensated power line, while in SSTI, a synchronous generator interacts with an actively controlled device in the grid. In SSCI, an actively controlled generator (wind turbine) interacts with a series compensated power line. Subsynchronous oscillations are also distinct from power system oscillations.

SSO causes significant stresses on electrical and mechanical parts of the system, because the amplitude of the oscillation will increase until something gives way. The turbine generator shaft is usually the weakest link in an interaction that involves a synchronous generator. Generator shaft damage is expensive to repair, and missiles resulting from shaft failure could hypothetically affect safety systems in an NPP.

SSR first occurred at Mohave coal power plant in 1970. Since then, it has been researched extensively, and SSO analyses are a routine part of HVDC, series compensation and power plant projects. Typical studies include mathematical analyses and electrical simulations. Simulations in particular are a more useful tool than before due to increased computational resources. SSO has been studied in nuclear power plant generators, as NPPs typically have large turbine generators that are susceptible to SSO. However, it does not appear to have been considered from a nuclear safety perspective before. Its potential effects on process systems have also not been analysed.

All three phenomena discussed in this thesis have been studied in the literature in varying detail, including using time based simulation methods. In ESSI, open phase conditions were studied from several different perspectives. However, existing simulation studies for both power frequency overvoltages and OPCs are limited to electrical system effects, with little attention paid to process systems and electrical protection and their feedback effects in the electrical system. Existing studies are also more interested in the steady state behaviour of the system rather than transient effects. Concentrating on researching these topics, COSI could bring novel insight into their effects on NPP systems and nuclear safety.

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