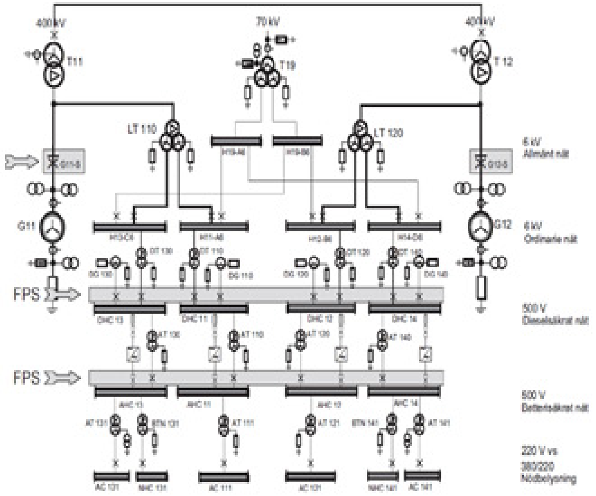

# Description of baseline simulation

Matti Lehtonen | Miro Rosenström | Seppo Hänninen | Poria Divshali |

VTT TECHNOLOGY 372

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# Preface

This work was carried out in the project ”COSI - Co-simulation model for safety and security of electric systems in flexible environment of NPP”. The research partners of COSI project are VTT and Aalto University. The work is follow up on request of SAFIR2022, The Finnish Research Programme on Nuclear Power Plant Safety 2019-2022. The work is motivated by the practical and theoretical problems studied in the project “ESSI- Electric systems and safety in Finnish NPP” of the previous SAFIR2018 programme.

The operating model of SAFIR2022 programme consists of a Management Board and four research area steering groups (SG) working under its supervision, as well as reference groups (RG) that are responsible for scientific and technical guidance of the projects. The administration of the programme is conducted by the administrative unit and Programme Director Jari Hämäläinen. COSI project belongs to “SG1 - Plant Safety and system approach to safety” and “RG2 - Plant level analysis”.

A project-specific steering group has also been set up for the COSI project, which will, among other things, direct research and resolve confidential issues related to the project, as the project uses power plant self-generated electrical system simulation models. The project-specific steering group consist of the following members: Seppo Härmälä (Chairman, TVO), Jyrki Kykkänen (TVO), Ari Kanerva (Vice chairman, Fortum), Juha Eriksson (Fortum), Juha Kemppainen (Fennovoima), Lauri Taivainen (Fennovoima), Monika Adsten (Energiforsk), Per Lamell (Forsmark/Vattenfall), Kim Wahlström (STUK), Samuli Hankivuo (STUK), Liisa Haarla (Fingrid), Minna Laasonen(Fingrid).

Thanks to Ari Kanerva for reviewing this report as official reviewer appointed by SAFIR 2022 RG2. Thanks to COSI steering group and to everybody that contributed to the projects taking part in interviews, email exchanges and reviewing and commenting the work.

Espoo 10.3.2020

# Authors Contents

# List of symbols

| | |
|---|---|
| AC | Alternative current |
| COSI | Co-simulation |
| DC | Direct current |
| DIDELSYS | Defence in Depth of Electrical Systems and Grid Interaction |
| EDG | Emergency diesel generator |
| EMTP-RV | Electromagnetic Transients Program - Recovery Voltage |
| ETAP | Electrical Transient Analyzer Program |
| FMEA | Failure mode and effects analysis |
| 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 | Nuclear Energy Agency |
| NPP | Nuclear power plant |
| NRC | US Nuclear Regulatory Commission |
| OECD | Organisation for Economic Co-operation and Development |
| OPC | Open phase condition |
| PSA | Probabilistic safety assessment |
| PSCAD | Power systems computer-aided design |
| PSS-E | Power System Simulation for Engineers |
| ROBELSYS | Robustness of Electrical Systems of Nuclear Power Plants |

| | |
|---|---|
| SAFIR2022 | Finnish National Research Programme on Safety of Nuclear Power Plants 2019–2022 |
| SBO | Station blackout |
| SSO | Subsynchronous oscillation |
| SSR | Subsynchronous resonance |
| SSTI | Subsynchronous torsional interactions |
| STUK | Säteilyturvakeskus (The Radiation and Nuclear Safety Authority) |
| TSO | Transmission system operator |
| VYR | The Finnish Nuclear Waste management Fund |
| YVL | Ydinturvallisuusohje (Nuclear safety guide) |

# 1. Introduction

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 equipment important to safety. 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 report 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 (Hänninen et. all 2019). 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 mitigating measures are needed, if any.

In this report, literature related to NPP electrical systems is reviewed. The literature focusses on electrical system reliability, electrical disturbances and simulation of electrical systems. This work 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 report describes the current state of research on these topics, and makes recommendations about simulating the conditions in COSI project.

This report discusses also the challenge of building the architecture of the COSI co-simulation platform in section 5. This issue was studied and reported in COSI Deliverable Divshali et al. (2020). The challenges are the data exchange layout among simulators, data exchange Intervals, time step handling and the protocol of data exchange between simulators. Here, an update on the challenges of Data exchange layout is added and also, a discussion about initialising of simulators is expressed.

# 2. Background and literature

## 2.1 General

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 systems important to safety also rely on electrical power for operation (Sandberg, J. (ed.) 2004).

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 of redundancy, diversity, separation, fail-safety and automatic startup. 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 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 (Hämäläinen & Suolanen 2019).

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 (Hänninen et. all 2019).

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 (Hänninen et. all 2019).

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 (Hänninen et al. 2019).

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 sub-synchronous resonance (SSR) modelling was also identified (Gomes et al. 2017).

## 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 (OECD 2017a) containing an analysis of relevant incident reports as well as discussions of 12 separate technical issues:

- 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 (OECD 2009).

Later, the DIDELSYS task group produced another report OECD 2013, 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 electrical systems important to safety. As a result, a paper OECD 2015a 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 OECD 2015a.

No further details on this topic are provided in the paper. However, the earlier DIDELSYS report OECD 2009 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 (OECD 2015a).

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 1) 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 OECD 2015b.

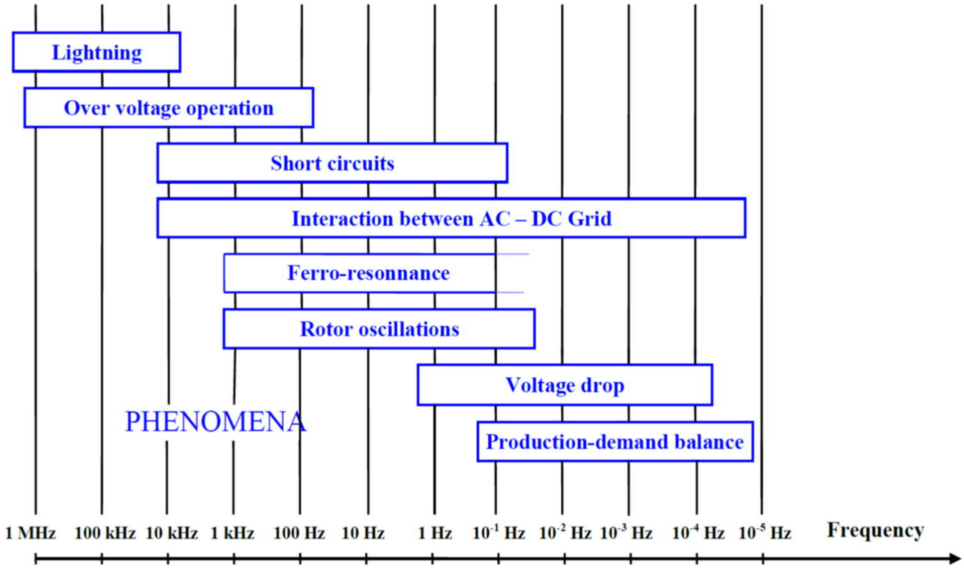

Figure 1: Electrical phenomena and their timescales (OECD 2015b).

## 2.5 Other literature

Wämundson et al. (2016) 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 off-site grid. 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 et al. (2016) considers four of these relevant:

- 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.

There are two 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 (Wämundson et al. 2016).

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 (2015) in their ROBELSYS paper (OECD 2015b).

Brück et al. (2018) 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.

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 (Brück et al. 2018).

## 2.6 Regulatory requirements

Nuclear safety regulation places certain requirements on electrical systems in NPPs and ENTSO-E grid codes for grid connections of power generating facilities (Fingrid 2018). In Finland, these requirements are detailed in YVL guides B.1 (STUK 2019a) and E.7 (STUK 2019b) 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 YVL B.1 are presented below and the corresponding number of paragraph of YVL B.1 is in the brackets.

- Systems 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 endanger the functioning of 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.

# 3. Some identified simulation cases

## 3.1 Power frequency overvoltages

The typical electrical disturbances discussed are overloading, lightning 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. The examination of the effects of failures will primarily focus on those systems for which STUK has issued requirements and which belong to some Safety Class.

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 (OECD 2015a), 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 (Pasonen 2018). 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 (Elovaara & Haarla 2011).

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.

Many studies into overvoltage events and other electrical transients appear to be inspired by the 2006 Forsmark event (described in section 3.3) 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 damage( OECD 2015a) 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. IEC 62855 provides the guidelines for analysis of AC and DC electrical power systems in nuclear power plants (NPPs). Analytical studies validate the robustness and adequacy of design margins and demonstrate the capability of electrical power systems to support plant operation for normal, abnormal, degraded and accident conditions. As such, the 2006 Forsmark event served as a reminder that a simple electrical transient, such as an overvoltage event, can potentially cause 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 (Brück et al. 2018)

Only few 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.

## 3.2 Open phase conditions

OPCs are typically caused by mechanical failures, such as conductor breaks or failed breaker poles. Individual breaker 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 (IAEA 2016).

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 (IAEA 2016). 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. Such 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 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 the work of Myrttinen (2019) 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.

## 3.3 Subsynchronous oscillations

Subsynchronous oscillations can be divided into three types depending on the devices participating in the oscillation: SSTI, SSR and SSCI (subsynchronous torsional interactions, subsynchronous resonance, and subsynchronous control interaction). Interactions between a synchronous generator and active devices in the grid, such as control systems of HVDC converters, are known as SSTI. In SSR, the oscillation occurs between a synchronous generator and a series compensated power line. SSR 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, SSR does not appear to have been analysed from a nuclear safety perspective before. And finally, recently discovered SSCI refers to interactions between control systems of wind power plants and other grid components.

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 and implemented. In Finland, analysis of subsynchronous oscillations in general started in the 1980s, when the Fenno-Scan1 HVDC link was being implemented near the Olkiluoto generators (Rauhala 2014). 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 SSR, if deemed necessary by the TSO (IEEE 1992).

Subsynchronous resonances 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 SSR. Time domain analysis allows very detailed simulations, including analysis of nonlinear effects (Kundur 1994, IEEE 1992).

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 (Kundur 1994, IEEE 1992, Suriyaarachchi et al. 2013). 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. The performance concerns of simulations are also diminished by the increasing computational power of computers (Rauhala 2014).

# 4. Co-Simulation Platform

In order to study precisely the simulation cases in Section 3, the interaction of electrical system and thermomechanical system of NPP must be considered. However, as discussed in the Divshali et al (2020). Architecture Design for NPP Co-Simulation Platform, the existing NPP simulator, e.g. Apros, cannot simulate the power system in details. Therefore, a co-simulation platform to simulate both electrical and mechanical system and their interaction is necessary.

## 4.1 Co-simulation architecture

In the Divshali et al (2020), the architecture and challenge of building a co-simulation platform are discussed in details under the following sub-section (Divshali et al. 2020):

- Data Exchange layout among simulators
- Data Exchange Intervals
- Time step handling
- Protocol of data exchange between simulators

Here, an update on the challenges of Data exchange layout is added, and also a discussion about initialising of simulators will be expressed.

### 4.1.1 Data Exchange Layout

In data exchange layout, the interactions between thermomechanical and electrical environments (both internal and the external electrical grids) of NPP must be determined. The main components that have interaction between these two environments are Pumps/Motors and Turbine/Generators.

The pumps are important component in NPP thermomechanical loops, which are energised by internal electrical systems of NPP. Therefore, any fault in the electrical system influence on the performance of the pump and consequently in thermodynamic loop. In the same way Turbine/generator set need to be simulated in both electrical and thermomechanical environment.

In order to simulate these component in two different environment and study their interaction, their model should be divided in three parts: Electrical part, Thermomechanical parts, and the Coupling. Hopefully, the swing equation, as shown below, can be used for coupling the Thermomechanical and electrical parts.

$$\begin{aligned}&\frac{d}{dt}\omega = \frac{1}{2H}\left(T_e - F\omega - T_m\right)\\&\frac{d}{dt}\theta = \omega\end{aligned} \tag{1.1}$$

where, $H$ is the combined motor and pump (or turbine and generator set) inertia coefficient; $T_e$ and $T_m$ are respectively electrical and mechanical torque; $F$ is friction coefficient and $\omega$ and $\Theta$ are angular velocity and angular position of coupling. Using Eq. (1.1), the electrical and mechanical system can be decoupled and simulated in two different software as explained in Divshali et al (2020).

The challenge is that the Eq. (1.1) is a differential equation and any small numerical error could lead to different final value, if it is solved in different simulators. Therefore, one simulator should solve this equation and send the angular speed to others. Here, since VTT developed Apros and access to the main code, it is disabled in Apros side and electrical simulators calculates the angular speed based on mechanical torque, which is calculated by Apros. Figure 2, shows the data exchange layout of motor pump.

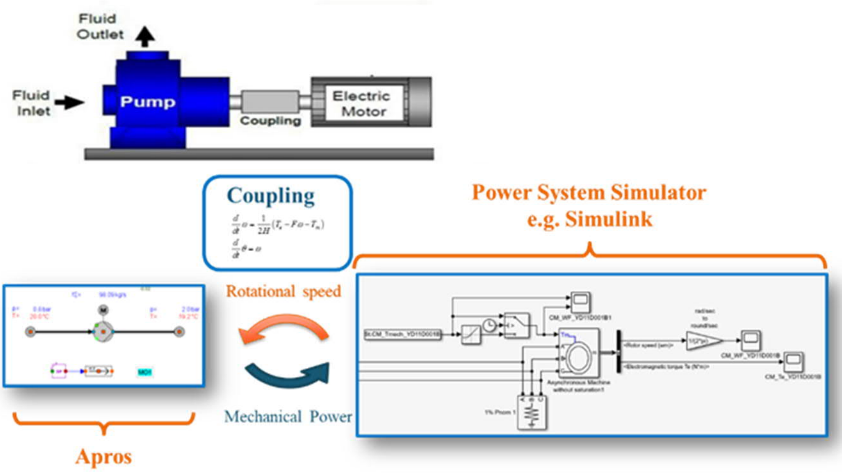

Figure 2. Data Exchange layout for pump/motor.

### 4.1.2 Initial condition

One of the challenge in co-simulating of a real NPP is starting simulation in a feasible operating point from perspective all simulators. If starting of the co-simulation has big deviation, like what Divshali et al (2020) has reported, the thermodynamic simulation may go to unstable point. In this situation, it is important to start all simulator from their steady state and initialising the data initial data exchange with the steady state values.

## 4.2 Interaction of Electrical system and mechanical system

In order to show the effect of electrical system on thermomechanical system, here a simple test is run by co-simulation of Apros and Matlab/Simulink.

The electrical system consists of an ideal upper grid, a generator and its controller, two motors and related transformers. The generator is coupled with a shaft, a turbine and a valve in mechanical side, which are modelled in Apros. The two motors are coupled to two pumps, whose mechanical parts are modelled in Apros, by basic pump and common pump models, respectively.

Both electrical system modelled in MATLAB/Simulink and thermomechanical system modelled in Apros are simple and just used for demonstration of the interaction. The block diagram of electrical system and thermomechanical system is shown respectively in Figures 3 and 4. As shown in Figure 4, the thermomechanical system does not include a complete loop and just has a node before and after each element with fixed temperature and pressure.

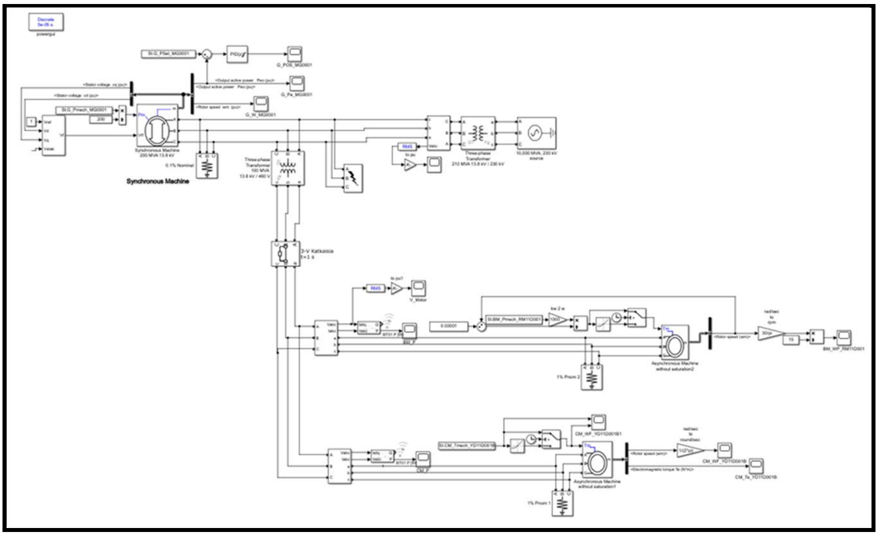

Figure 3. The Simulink model of the test case.

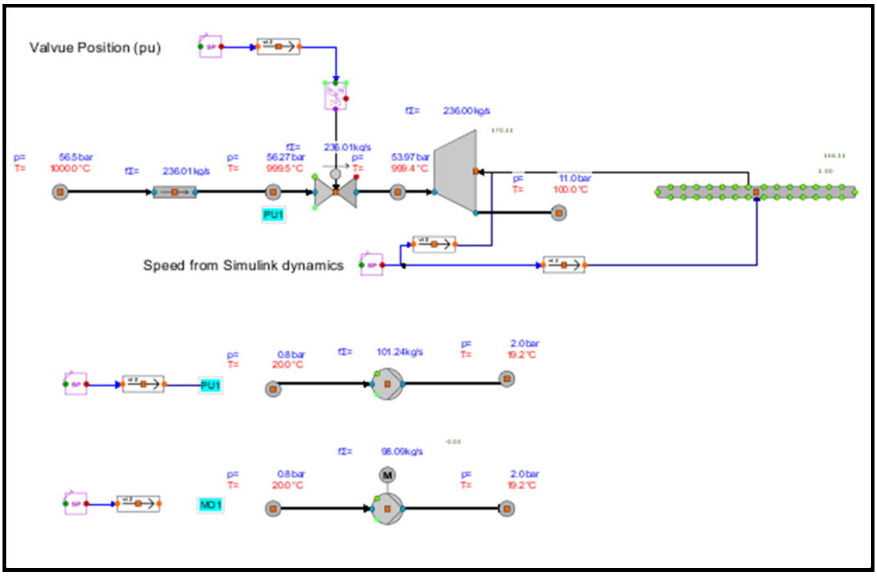

Figure 4. The Apros model of the test case.

In the electrical system, a 3 phase fault happens at t=3 s. This fault leads to voltage drop in the motor terminals and decrease in electrical torque and speed. Figure 5 shows the voltage at motors terminals. Figure 6 and 7 shows the behaviour of basic pump and common pump in Apros using the developed co-simulation platform.

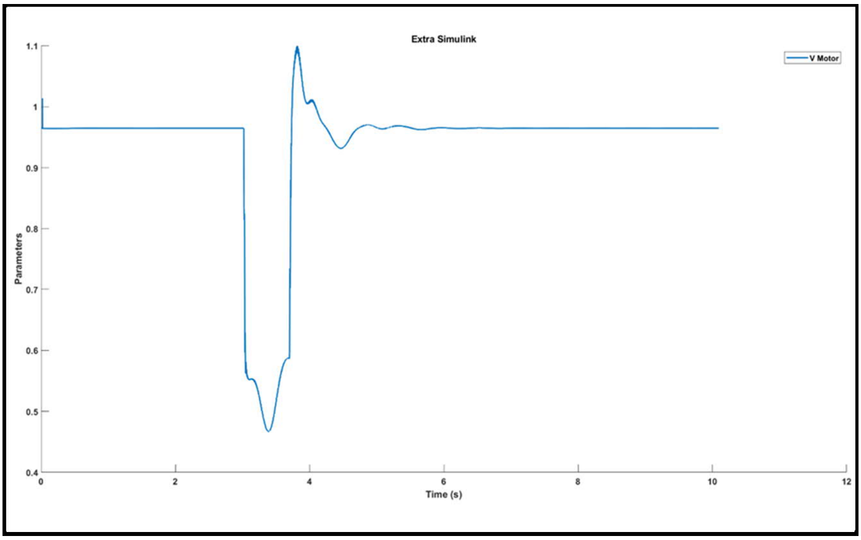

Figure 5. The Voltage of motors' terminals, simulated in Matlab/Simulink.

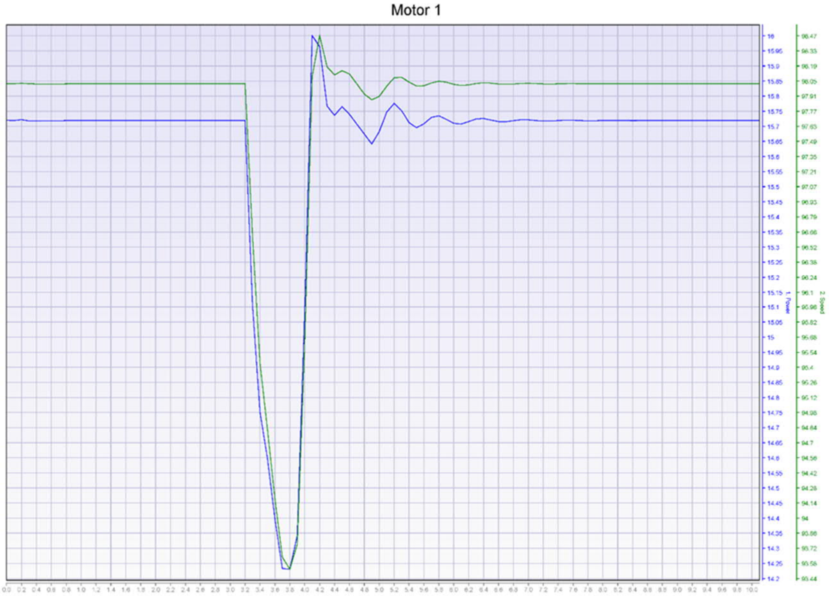

Figure 6. The mechanical power (kW) and angular speed (%) of the basic pump, modelled in Apros and coupled to asynchronous motor, modelled in Simulink.

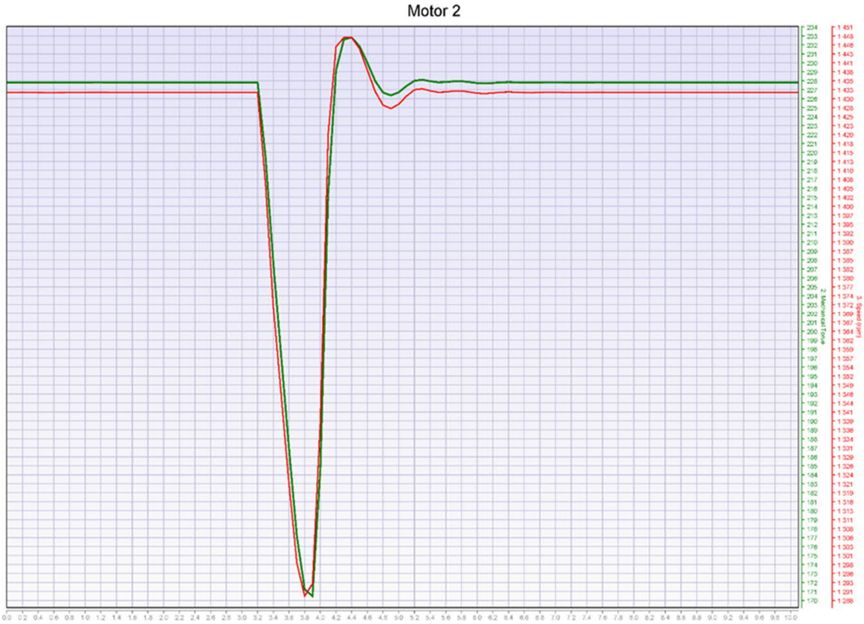

Figure 7. The mechanical torque (kW) and angular speed (rpm) of the common pump, modelled in Apros and coupled to asynchronous motor, modelled in Simulink.

As shown in Figure 6 and 7, the voltage drop lead to decrease in angular speed and mechanical power/torque. These sudden reductions in the mechanical power and speed results in decrease in mass flow as it can be seen in Figure 8. The mass flow variation in a loop may lead to change in temperature and pressure of the loop and even unstable situation.

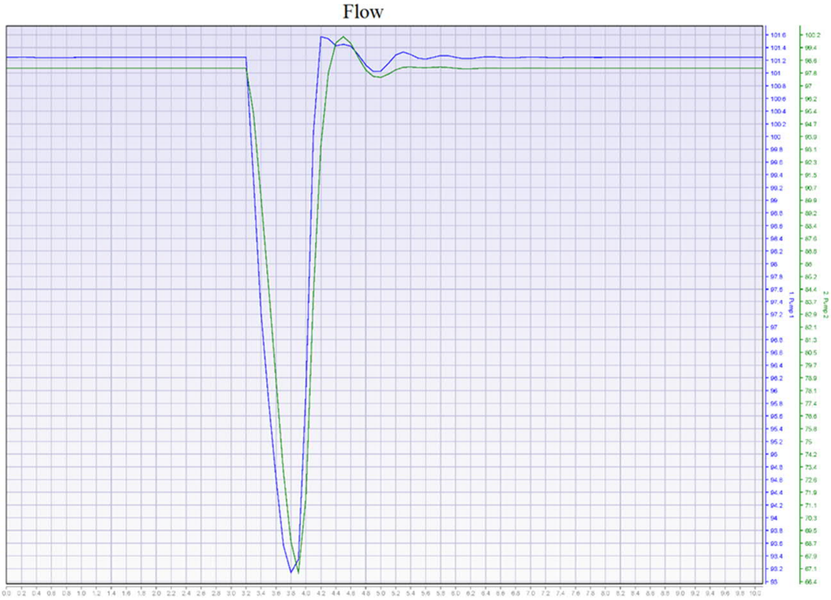

Figure 8. The mass flow of two pumps, modelled in Apros and coupled to asynchronous motors, modelled in Simulink; a three phase fault at t=3 s.

In generator side, there is also an interaction between mechanical and electrical environments. Figure 9, shows the mechanical power, valve, position and angular speed of turbine/generator set during the fault using the developed co-simulation platform.

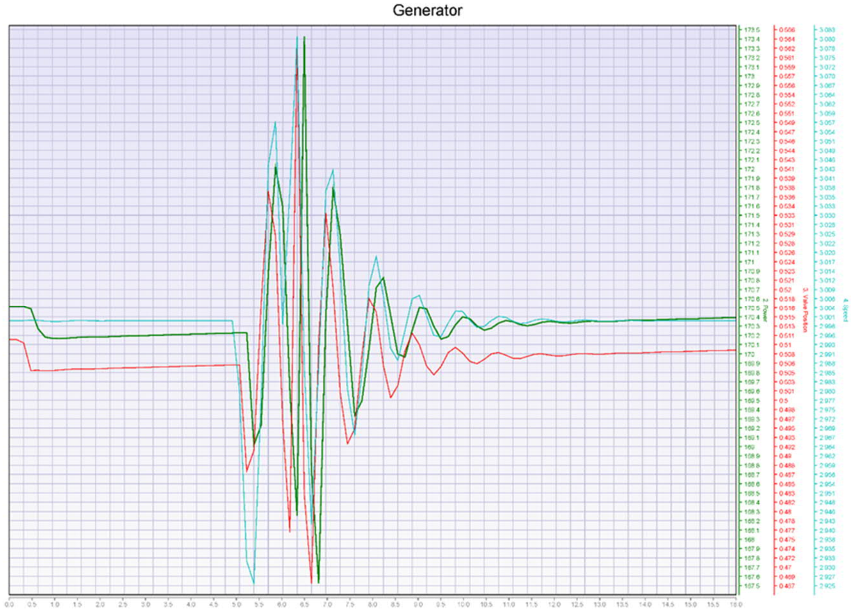

Figure 9. The mechanical power, valve, position and angular speed of turbine/generator set during the fault at t = 3s using the developed co-simulation platform.

# 5. Conclusions

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 the 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 report reviewed relevant literature and described 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 start-up and short circuit analyses. 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 discuss simulations at the Swedish Forsmark and Oskarshamn plants (OECD 2015a, OECD 2015b), while Brück et al. (2018) 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 may cause 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 and neutral point treatment 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 the 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 may cause 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 report have been studied in the literature in varying detail, including using time based simulation methods. In the ESSI project, 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. In the literature, 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.

The challenge of building the architecture of the COSI co-simulation platform covers the data exchange layout among simulators, data exchange Intervals, time step handling and the protocol of data exchange between simulators. These issues were studied earlier in the COSI deliverable Divshali et al. (2020). Here, an update on the challenges of Data exchange layout is added and also, a discussion about initialising of simulators is expressed.

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| | |
|---|---|
| Title | **Description of baseline simulation** |
| Author(s) | Matti Lehtonen, Miro Rosenström, Seppo Hänninen & Poria Divshali |
| 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.<br>This report 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 report makes recommendations about simulating these conditions in COSI project. COSI is a research project which aims to develop a co-simulation platform for simulating the electrical system and NPP process systems together.<br>This report 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.<br>The challenge of building the architecture of the COSI co-simulation platform covers the data exchange layout among simulators, data exchange Intervals, time step handling and the protocol of data exchange between simulators. Here, an update on the challenges of data exchange layout is added and also, a discussion about initialising of simulators is expressed. |
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| | |
|---|---|
| Nimeke | **Perussimuloinnin kuvaus** |
| Tekijä(t) | Matti Lehtonen, Miro Rosenström, Seppo Hänninen & Poria Divshali |
| Tiivistelmä | Sähköjärjestelmät toteuttavat ydinvoimalaitoksessa erilaisia toimintoja, ja niitä tarvitaan monien turvajärjestelmien toimintaan. Normaalissa käytössä kaikki sähköjärjestelmät on kytketty toisiinsa siirtoverkon jännitetasolla, mikä luo mahdollisuuden yhteismuotoisiin vikoihin, jotka johtuvat laitoksen sisäisestä tai ulkoisesta sähköjärjestelmästä. Itse asiassa useita tällaisia tapauksia on tunnistettu. Tässä raportissa tarkastellaan kirjallisuuskatsauksen avulla ydinvoimalaitoksen sähköjärjestelmän luotettavuutta ja häiriöitä. Kolme erityisen merkityksellistä vikatapausta (tehotaajuiset ylijännitteet, vaihekatkos ja aliharmoninen värähtely) valitaan perusteellista analyysiä varten.<br>Kirjallisuuskatsauksen ja analyysien perusteella tämä raportti antaa suosituksia näiden olosuhteiden simuloimiseksi COSI-projektissa. COSI on tutkimusprojekti, jonka tavoitteena on kehittää yhteissimulointialusta sähköjärjestelmän ja ydinvoimalaitoksen prosessijärjestelmien simuloimiseksi yhdessä. Tässä raportissa todetaan, että nykyisissä sähköjärjestelmien simulaatiotutkimuksissa ei ole otettu yksityiskohtaisesti huomioon prosessijärjestelmän vaikutuksia ja muuta ohimenevää dynamiikkaa ja että COSI voisi tarjota näkemyksen niiden vaikutuksista ydinturvallisuuteen.<br>COSI-yhteissimulointialustan arkkitehtuurin rakentamisen haasteena on simulaattorien välisen tiedonvaihdon suunnittelu, tiedonvaihdon aikavälit, simuloinnin aika-askelluksen käsittely ja simulaattoreiden välinen tiedonvaihtoprotokolla. Tähän raporttiin on lisätty myös päivitys tiedonvaihtosuunnittelun haasteista ja pohdittu myös simulaattoreiden simuloinnin käynnistämisen alkutilannetta. |
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| Sivumäärä | 37 s. |
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| Rahoittajat | Valtion ydinjätehuoltorahaston (VYR), Aalto yliopisto, Energiforsk (Ruotsi), Fingrid Oyj ja VTT Oy |
| Avainsanat | Ydinturvallisuus, sähköjärjestelmät, simulointi, tehotaajuiset ylijännitteet, vaihekatkos, aliharmooninen värähtely |
| Julkaisija | Teknologian tutkimuskeskus VTT Oy<br>PL 1000, 02044 VTT, puh. 020 722 111, https://www.vtt.fi/ |

## Description of baseline simulation

The COSI project belongs to SAFIR2022 research programme and it studies safety design principles of electrical systems in the nuclear power plant focusing on selected topics considered most relevant for the stakeholders on the three levels of design: 1) plant level safety design, 2) systems safety design, and 3) component safety design. To provide support for safety analyses, COSI project will develop a co-simulation platform for simulation of the electrical systems and NPP process systems together. This report 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 report makes recommendations about simulating these conditions in COSI project. This report notes that existing electrical simulation studies have not considered feedback effects of the process system and other transient dynamics in much detail, and that COSI could provide insight into their effects on nuclear safety.
The challenge of building the architecture of the COSI co-simulation platform covers the data exchange layout among simulators, data exchange Intervals, time step handling and the protocol of data exchange between simulators. This report includes also an update on the challenges of data exchange layout and a discussion about initialising of simulators.

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