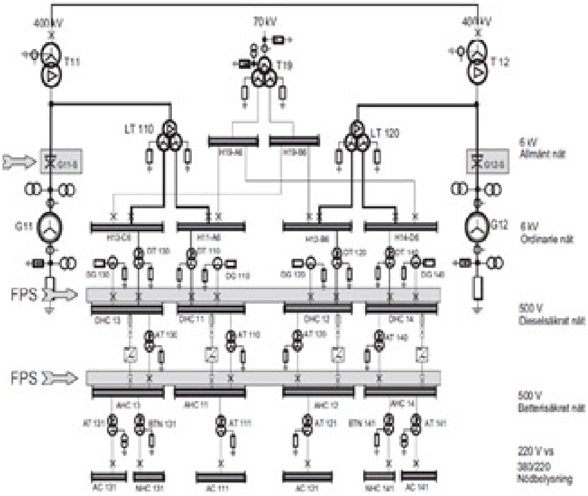

Safety case of electric systems in NPP for co-simulation

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VTT TECHNOLOGY 370

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ISBN 978-951-38-8727-8

VTT Technology 370

ISSN-L 2242-1211
ISSN 2242-122X (Online)
DOI: 10.32040/2242-122X.2020.T370

JULKAISIJA – PUBLISHER

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FI-02044 VTT, Finland
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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 Lauri Taivainen for reviewing this report as official reviewer appointed by SAFIR 2022 RG2. Thanks also to Liisa Haarla, Fingrid for her suggestions to amend the text. I would like to thank also Ilkka Karanta and Atte Helminen (VTT) for taking part in the interview on probabilistic reliability analysis issues (PRA). 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 31.2.2020
Authors

Contents

List of symbols

AC	Alternative current
COSI	Co-simulation
DC	Direct current
DDSO	Device dependent subsynchronous oscillation
DEC	Design Extension Conditions
DiD	Defence in depth
DIDELSYS	Defence in Depth of Electrical Systems and Grid Interaction
EDG	Emergency diesel generator
EIFIS	Energimarknadsinspektionens författningssamling (Swedish Energy Markets Inspectorate's constitutional collection)
EMTP-RV	Electromagnetic Transients Program - Recovery Voltage
EPRI	Electric Power Research Institute
ETAP	Electrical Transient Analyzer Program
FMEA	Failure mode and effects analysis
HVDC	High voltage direct current
IAEA	International Atomic Energy Agency
LOCA	Loss of coolant accident
LOOP	Loss of offsite power
MTTR	Mean time to repair
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
NRC	US Nuclear Regulatory Commission
NUREG/CR	Nuclear Regulatory Commission/Contractor report

OECD	Organisation for Economic Co-operation and Development
PSA	Probabilistic safety assessment
PRA	Probabilistic risk assessment
PSCAD	Power systems computer-aided design
PSS-E	Power System Simulation for Engineers
RfG	A network code on requirement for grid connection of generators
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
SC	Safety Class
SSO	Subsynchronous oscillation
SSR	Subsynchronous resonance
SSTI	Subsynchronous torsional interactions
STUK	Säteilyturvakeskus (The Radiation and Nuclear Safety Authority)
SvKFS	Svenska Kraftnäts föreskrifter (Svenska Kraftnet regulations)
WENRA	Western European Nuclear Regulators Association
YVL	Ydinturvallisuusohje (Nuclear safety guide)

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 processes and control systems, and operation of various safety systems (Sandberg, J. (ed.) 2014). 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 (DiD) 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 the first deliverable of Work package 3 (WP3) of the 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 al 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.

The WP3 of the COSI project studies the safety assessment of electric systems of NPP. Design principles in NPPs are a collection of laws, guidelines and considerations that a designer aims to follow in the design of a system. Safety principles are normally given in the relevant regulations and standards (STUK 2019a–2019c, IAEA 2016). The experience from the nuclear sector is that there is a continuous need to reconsider safety design principles. This is due to operating experience (occurred accidents and incidents), general tendency to aim for safety improvements, international harmonisation of regulation, but also to look at economical aspects of nuclear power. We distinguish the three levels of design: 1) plant level safety design, 2) systems safety design, and 3) component safety design.

Since the full scope of issues is vast, COSI will focus on selected topics considered most relevant for the stakeholders. At plant level, the aim is to outline a general approach for a safety case (ONR 2016) dedicated to electric systems events. Term “safety case” is deliberately used here instead of safety analysis report to emphasize the safety demonstration (claim-argument-evidence) aspect of the safety assessment. WP1 & WP2 of COSI project are connected to this target, since an essential tool for assessments is plant level model that is capable to analyse events, i.e. for the deterministic safety analysis (DSA) (IAEA 2009). PRA is another relevant tool (Sparre et al. 2008, Stiller et al. 2018). The combined argumentation in the safety case shall be thus based both on deterministic and probabilistic argumentation (IAEA 2011), which will be demonstrated with suitable cases. For utilities, this study will provide a good praxis example for safety assessments. For safety authorities, the results can be used to support reviews of safety assessments.

At power system level, the aim is to analyse how well redundancy, diversity and separation principles are actually accomplished for electric systems of NPP. The challenge is that electric systems are vital support systems for most safety functions. Ideal DiD principle (WENRA 2013, 2014) may not be possible and compromises can be needed. Whether such compromises can be accepted, it could be assessed by PRA (IAEA 2010). At component level, the aim is to study how system level requirements are reflected in selected components, e.g., related to demands of flexible operation. Component level studies are however left later in the project, and there is no such task in 2019.

The work of WP3 will start with definition of “Overall safety case for electric systems (T3.1)” by investigating events related to electric systems. Analysis of electrical events follows about the same approach both in deterministic and probabilistic safety assessments. In the later stage, the focus will be in the safety functions and systems and component level consideration. The results of this task will be used in WP1 to plan the types of electrical events that should be able to simulate. In the following years (2020–2021), the focus is shifted from electrical events towards safety functions and systems level considerations. At system level, the aim is to study how plant level requirements are propagated and allocated to electric systems. This includes identification of link to DiD, application of redundancy, separation and diversity principles, safety classification (IAEA 2014, 2016b), Technical Specification requirements, role of manual interventions, status of system in various plant operating states, etc. There are various measures by which robustness in electrical systems can be improved (Lindahl et al. 2018).

According to the ORN (2016) the nuclear safety case is defined as follows:
“A safety case is a logical and hierarchical set of documents that describes risk in terms of the hazards presented by the facility, site and the modes of operation, including potential faults and accidents, and those reasonably practicable measures that need to be implemented to prevent or minimise harm. It takes account of experience from the past, is written in the present, and sets expectations and guidance for the processes that should operate in the future if the hazards are to be controlled successfully. The safety case clearly sets out the trail from safety claims through arguments to evidence.”

In our case, we consider the safety case during the operation stage of facility life cycle. According to the work plan, the task T3.1 starts the definition of safety case by studying faults and disturbances related to internal and external? electric systems. This includes identifying and classification of types of plant external and internal events related to electric systems. In 2019, T3.1 will perform a literature study, compilation of occurred events from available data sources and an information collection from the utilities. The aim is not to provide a complete compilation of possible events related to electric systems, but to show an illustrative example, which is then used as an input to the safety case. Target of 2019 work is namely to outline a safety case that demonstrates that the analysis of electrical events is sufficiently complete and correctly categorised. “Outline of a safety case” means that the type of claims and subclaims and associated sources of evidence will be considered in this task.

As a background work for this deliverable is the Master thesis in Aalto University (Rosenström 2019), which was done in the COSI project. Section 2 “Background and literature” covers the literature survey and it is part of the aforementioned Master thesis. In Section 2, the literature related to NPP electrical systems is reviewed. The literature focuses on electrical system reliability, electrical disturbances and simulation of electrical systems. Section 2 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 review and an analysis of these conditions, this report describes the current state of research on these topics. In detail, Sub-section 3.1 briefly describes the role of electrical systems in an NPP and the design principles applied to them. Sub-section 3.2 reviews previous work done under the SAFIR programme. Sub-sections 3.3 through 3.5 review literature related to electrical systems and disturbances in general, while Sections 3.6 and 3.7 describe seven certain specific requirements related to NPP electrical systems.

Section 3 considers the safety case for electrical systems of NPP. In our case, we consider the safety case during the operation stage of facility life cycle. The aim is not to provide a complete compilation of possible events for the safety case related to electric systems, but to show important illustrative examples, which form the safety case. Some of events will be selected later for the analyses by simulation using the COSI simulation platform. The events and disturbances that are included in the safety case base on the literature survey presented in section 2. They are compilation of occurred events reported by utilities in the available data sources. Finally, Section 4 ends the report with final conclusions and a summary of the topics discussed.

2. Background and literature

2.1 General

Used nuclear fuel contains a significant number 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 (Sandberg, J. (ed.) 2004).

More specific design philosophies, applied to the design of safety critical systems, are redundancy, diversity and separation in particular for internal faults of NPP. Fail-safety and automatic startup are also applied. 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) (Sandberg, J. (ed.) 2004).

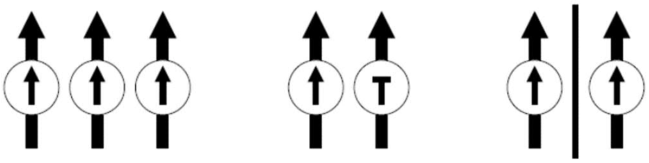

Figure 1. Design principles for safety systems: redundancy (left), diversity (centre), separation (right).

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 (Sandberg, J. (ed.) 2004).

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 various NPP 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 (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 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), (SAFIR 2018).

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, large lightning strikes and flexible operations. The project produced several reports and articles on these topics (Hämäläinen, J., Suolanen, V. (eds.) 2019).

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

Kulmala and Alahäivälä (2018) expand on the previous report, providing more details on the topics discussed previously. In particular, they concentrate on the effects of open phase condition in the NPP electrical system, and on the detection of open phase conditions. 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 open phase condition and that no critical safety issues were discovered. The findings are also summarised in a conference paper (Kulmala, A., Alahäivälä, A., 2019).

Alahäivälä, A., Lehtonen, M. (2018) studied the effects of open phase conditions 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 open phase condition, and that the motor can operate at least for a few minutes during an open phase condition without overheating.

Rizk et al. (2018) 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. Lehtonen et al (2019) 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.

Subedi and Lehtonen (2019) 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. The transmitted transient overvoltages varied depending on which voltage levels the surge arresters were installed, and found that all surge arresters significantly reduced the overvoltages transmitted to the medium voltage levels. Gürbüz (2018) also simulated the effects of lightning on power plants in his-Master's thesis. They based their models on real NPP electrical systems and modelled the system in more detail. Pasonen (2018) studied the effects of lightning transients on low voltage AC and DC systems in NPPs. Pasonen (2018) simulated how the model responded to the kind of transients described by Subedi and Lehtonen, and how overvoltage suppression devices, capacitors and batteries in the low voltage system affected the response.

Holmgren (2008) and Pasonen (2017) 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. The plant operators see that flexible operation cause stresses to thermal systems, turbine and fuel rods, disturbance sensitivity of power station, the electrical components and ICT systems can increase. It cause also ageing of certain operational components and an increase in the maintenance work and cost. 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 (2018) 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 Finnish TSO Fingrid, 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 (Hänninen et al 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 simulation model of the dynamic external grid equivalent that has the right dynamic properties 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 events of electrical system that should be included in the safety analysis of an NPP. COSI continues the work on open phase conditions and flexible operation started in ESSI. However, lightning strikes have been excluded from COSI due to the very different timescales involved (Hänninen et al 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 2009) 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 (OECD 2009).

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

- grid challenges
- communication between NPP and grid operators
- NPP 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 safety related electrical systems. 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 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 (OECD2015b).

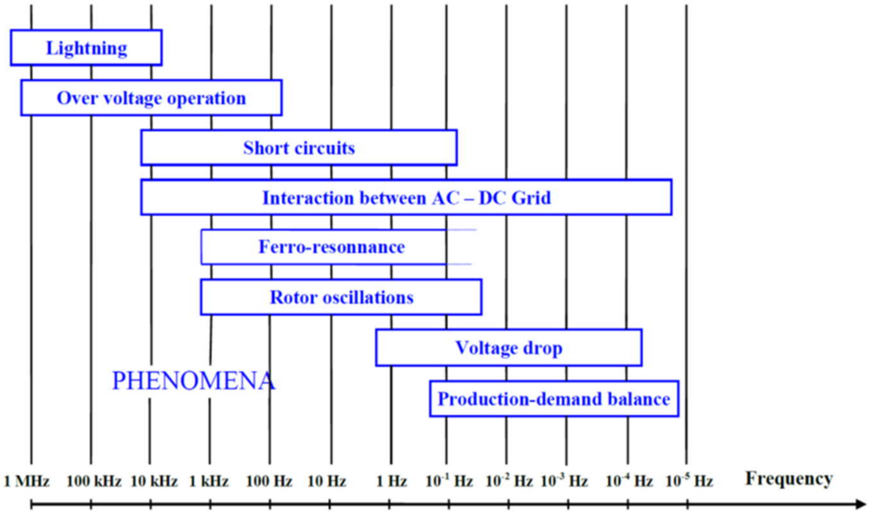

Figure 2. Electrical phenomena and their timescales (OECD 2015b).

Svensson et al. (2015) propose a procedure for grid and NPP 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 (OECD 2015b).

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 inside NPP 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 reactive power support 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 (OECD 2015b).

Lamell (2015) 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 nominal 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 (open phase condition) event, where safety functions failed due to the open phase condition, but the fault was not automatically disconnected.

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 external 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 (OECD 2015a).

Kim and Jeong (2015) 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.

Khandelwal and Bowman (2015) discuss the simulation of open phase conditions (open phase condition). Investigation into open phase condition s was inspired by two separate events in Byron in 2012. In one of the events, the open phase condition was not detected automatically and caused safety related and other components to trip, similarly to the 2013 Forsmark event. Several factors affect how an open phase condition 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.

The authors note that there are two aspects to open phase condition analysis: acceptability, which is the ability to function during an open phase condition, and detectability, which is the ability of protection systems to detect the open phase condition and disconnect the fault. The effects of two factors on the acceptability and detectability of open phase condition 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 open phase condition and the light green area a detectable open phase condition, while the yellow and red areas represent situations where problems are expected. One of the findings of the study is that detection of open phase conditions can be difficult or impossible in some cases, particularly with only phase voltage measurements (OECD 2015 b).

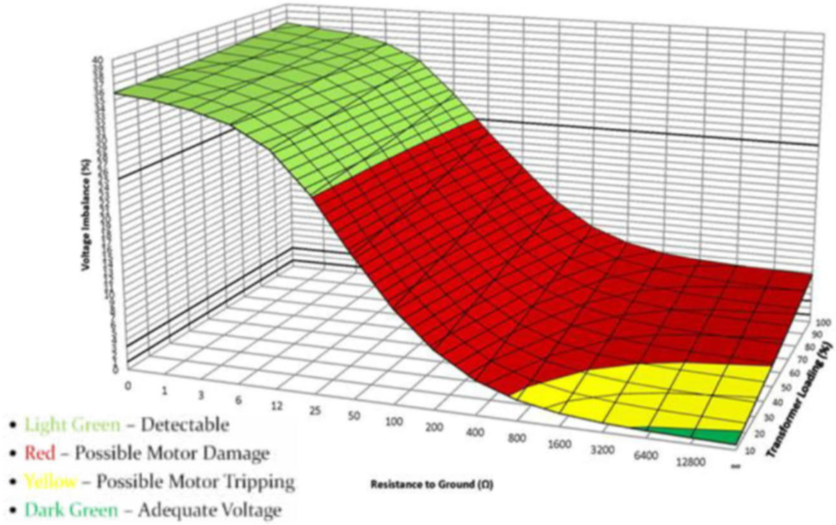

Figure 3. Voltage unbalance vs. fault impedance and transformer loading in open phase condition according to Khandelwal and Bowman (2015).

2.5 Other literature

Duchac and Noël (2011) 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 (Duchac & Noël 2011)

In his Master's thesis, Hankivuo discusses methods to prevent common cause failures due to electrical grid disturbances in NPPs. He describes 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 strikes, short circuits, ground faults and open phase condition. These disturbances can potentially cause overvoltages, undervoltages, overcurrents, phase unbalance as well as frequency deviations in the electrical system (Hankivuo 2011).

Wämundson (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. 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.

- 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 open phase condition events, as well as several cases where grid protection systems operated incorrectly (Wämundson 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 open phase condition 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 (Wämundson 2016).

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 open phase condition incidents, but that other electrical failures were also included. They list 10 open phase condition 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 open phase condition 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. 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.

- 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, which the system is not expected to deviate from even during significant disturbances (Fingrid Oyj 2018).

Similarly, the allowed voltage range in the 400 kV network in Finland is from 360 kV to 420 kV (Fingrid Oyj 2018). 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 the trips of generators after 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 countries. 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. It should be pointed out that the reference to the grid codes for Sweden refers to the old situation before the 27th April 2019. The old code is still valid for those plants designed before this date. For new plants the European commission code Rfg together with Swedish code amendment EIFS 2018:2 is valid. For instance the fault clearance time as pointed out for the old code (SvKFS 2005:2) was 250 ms whereas the new code states 200 ms (EIFS 2018:2).

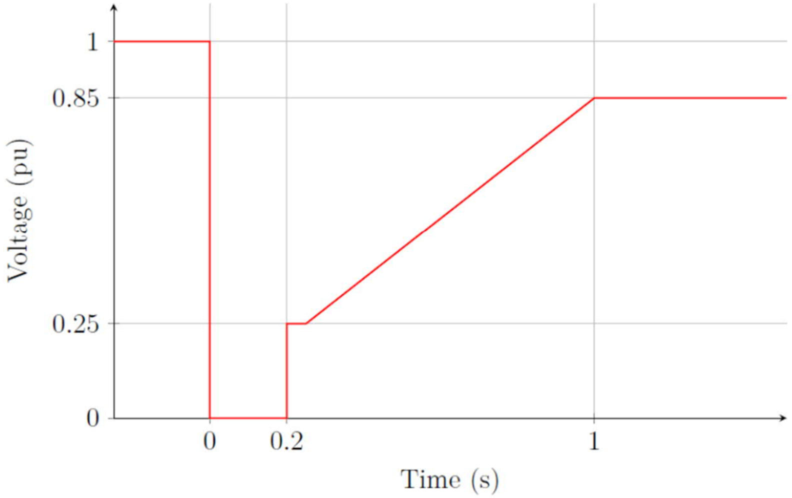

Figure 4. Fault-ride-through voltage profile in Finnish transmission grid for large generators (Fingrid Oyj 2018).

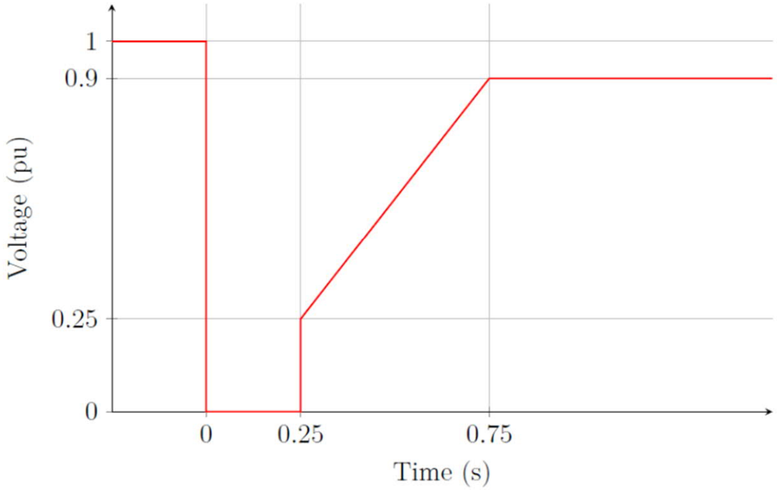

Figure 5. Fault-ride-through voltage profile in Swedish transmission grid for large generators (Svenska Kraftnät 2005).

3. Safety case for electrical systems of NPP

3.1 General

According to the work plan of the COSI task T3.1, this section considers the safety case for electrical systems of NPPs. In our case, we consider the safety case during the operation stage of facility life cycle. The target of 2019 work is namely to outline a safety case that demonstrates that the analysis of electrical events is sufficiently complete and correctly categorised. The aim is not to provide a complete compilation of possible events for the safety case related to electric systems, but to show important illustrative examples, which form the safety case and some of them will be selected later for the analyses by simulation using the COSI simulation platform. The events and disturbances that are included in the safety case base on the literature survey presented in section 3. They are compilation of occurred events reported by utilities in the available data sources.

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.

3.2 Safety classification of electric systems in NPP

The nuclear facility's systems, structures and components are grouped into the Safety Classes 1, 2 and 3 and Class EYT (non-nuclear safety) on the basis of their importance for safety. Safety Classification of the nuclear facility's systems, structures and components are primarily be based on deterministic methods supplemented, and complemented by a Probabilistic Risk Assessment (PRA) and expert judgement, STUK 2019d. The main principles of the safety classification and the categorization of electric systems are as follows based on their importance.

1. Safety Class 1 (SC1). Nuclear reactor cooling circuit (primary circuit) shall be assigned to SC1. There are no actual power systems of safety class SC1.
2. Safety Class 2 (SC2). Systems accomplishing safety functions and their necessary support systems shall be assigned to SC2, if they are designed to provide against postulated accidents to bring the facility to a controlled state and to maintain this state. Those electric systems belongs to SC2, which ensure the Safety Class 2 functions. These structures and components include among others main components of the emergency core cooling system for reactor decay heat removal. For example the emergency

diesel generators and the network supplied by diesel generator belong to SC2.

3. Safety Class 3 (SC3) includes those electric systems, which ensure Safety Class 3 functions. It covers among others the electric distribution systems and power supply units. These systems include among others the cooling of the reactor, systems designed to bring the facility into a controlled state after a severe reactor accident, systems designed to control reactor power, pressure or make-up water, mitigate the consequences of operational occurrences unless they are assigned to a higher safety class for some other reason
4. Safety Class EYT (non nuclear safety) includes the systems which don't belong to SC1, SC2 and SC3. The system protects systems that perform safety functions from internal or external events, such as fire prevention systems and systems implementing security arrangements; system is necessary for bringing the facility to a controlled state and onwards to a safe state in case of events involving a design basis category DEC combination of failures (DEC B) or a rare external event (DEC C); system is necessary for bringing the facility from a controlled state to a safe state after a severe reactor accident and for maintaining it.

The safety case covers the whole chain of electric systems enabling the structured approach for evaluation of possible common cause failures and design principles. These enables also evaluation the adequacy and balance of safety requirements. The general main principle is that the external and internal system for supplying power to the plant unit shall be designed to ensure that each of them has sufficient capacity to power the safety functions independently in accordance among others: removing decay heat generated in the reactor, ensuring the integrity of the primary circuit and maintaining the reactor in a sub-critical state (STUK. 2019a). More specific design philosophies, applied to the design of safety critical systems, are redundancy, diversity, separation, fail-safety and automatic start-up as presented in section 3.1. The following subsections covers important disturbances or faults for analysis of the safety case. The general requirements of STUK are set out at the beginning of each sub-section dealing with such disturbances.

3.3 Proposed disturbances and faults of the safety case

3.3.1 Lightning overvoltages

STUK (2019a) sets the general requirements for earthing and lightning protection among others in the following points:

"5460. When the EMC requirements are defined, due consideration shall be given to the exposure of components to potential recurring rapid transients (such as the switching off of inductive loads and the ringing of relays) and high-energy transients (such as various switching transients and strokes of lightning).

5467. Earthing and lightning protection systems shall be designed, installed and maintained so as to effectively protect people, buildings, equipment as well as electrical and I&C systems from overvoltage and overcurrent caused by strokes of lightning and other potential electromagnetic interference due to meteorological conditions.
5468. The nuclear power plant's earthing and overvoltage protection systems shall be designed to effectively prevent the occurrence of harmful on-site or off-site overvoltage in electrical and I&C systems.
5469. When earthing and overvoltage protection is designed, electrical systems shall be understood as a single entity because insufficient protection of even one part of the system may expose other systems to disruptions."

The impacts of lighting overvoltages were preliminary studied in the previous ESSI project of SAFIR 2018. Direct lightning strokes to the phase conductor of the connected line and back flashovers resulting from the lightning stroke to the transmission tower or shield wire injects wave current with high amplitude to the phase conductors and eventually through the transformer from external grid to the internal electrical systems of NPP (Subedi, D., Lehtonen, M. 2019). In the case of large wide area grounding system and high soil resistivity, the ground potential rise may cause high voltage stress in the connected equipment. One of the critical situations is the lightning strike to the gantry or adjacent transmission tower of a large power generating station. A large lightning current may cause ground potential rise (GPR) and huge potential differences between different grounded parts of the electrical systems. In the extreme case, these differences may cause excessive stress to the insulation of the signal cables of the automation and control systems. These voltage stresses may be mitigated by adding to the grounding system external conductive cables parallel to the protected signal cables. In addition, surge protective devices may be needed in most critical locations. Planning such a protection requires a detailed analysis of the grounding system and electrical system lay out, as well as investigation of the different routes along which the lightning current may enter the plant. It might be necessary to limit the possible lightning entering routes by using lightning rods (Rizk et al 2018). Related to studying the effects of GPR, it may be possible that some electronic systems are disconnected from the network by the effect of the lightning current. For those cases, the simulation model could investigate the behaviour of the plant in such unexpected subsystem "black-outs".

NPPs are generally considered to be well protected against transient overvoltages. Also the COSI simulation platform is not designed for so fast transient analyses."

3.3.2 Short circuit, ground and open phase faults

STUK (2019a) sets the general requirements for electrical failures and protection among others in the following points:

"5407. The propagation of faults from one redundant electrical system part to another via cross-connections shall be reliably prevented.

5470. The electrical power systems shall be provided with reliable protection devices that, in the event of disturbances and failures, only deactivate the affected component or section of the electric power network (selectively) under any foreseen grid switching condition.
5471. Fault currents shall be cut off quickly enough to avoid hazards and to minimise disruptions."
5474 5474. Adequate logging devices shall be provided to monitor the power distribution network to ensure that any electrical disturbances are promptly detected, located and repaired."

3.3.2.1 Overvoltages

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.

3.3.2.2 Double earth fault

Sometimes a double earth fault can occur in the network. This means that in the same galvanically interconnected network, there are two different earth faults in different phases simultaneously. A double earth fault usually occurs as a result of a 1-phase earth fault, where the voltages of two healthy phases rise. As a result of this increased voltage, the insulation of the intact phase will no longer withstand any weak point. Then a new earth fault will occur in the new location. This type of fault is particularly dangerous because it is not known which route the current will return to its starting point. Double earth fault causes high currents in grounded parts and can damage low voltage circuits and control and signal cables in particular. In practice, double earth faults can occur only in the medium voltage network where the neutral point is isolated or earthed with Petersen coil. This kind of faults and their impacts are possible to analyse using the simulation platform.
Open phase conditions

ESSI project (SAFIR2018) studied different alternatives for detecting the open phase condition situation and their suitability for different types of open phase condition situations. The currently used protection methods and operating procedures were analysed and recommendations about how to improve the security of NPPs in the case of open phase condition were formulated. Detection of open phase condition s is not straightforward, because transformers and motors re-generate voltage, and the unbalances can remain at a level, which is not detected by protection. Transformers between the faulted point and the point of interest affect significantly the observed voltages and currents. The most severe locations for open phase condition are the main generator bus, primary side of the unit transformer and primary side of the standby transformers. From open phase condition detection point of view, the most challenging open phase condition occurs when the NPP is supplied from the external grid, the main generator is disconnected i.e. transformer loading is low and the single open phase is on the primary side of the unit or standby transformer. The resulting unsymmetrical system affects the different NPP electrical system components in various ways, which is summarized in Table 1. The table also presents the potential NPP component protection functions that might operate in open phase condition situations. Several alternative methods for open phase condition detection exist and the selection of the most suitable methods for a particular NPP depends on the NPP characteristics. The preparedness of Finnish NPPs against open phase condition can be considered good and no critical safety risks were identified during this research (Hämäläinen & Suolanen 2019).

Table 1. Effects of open phase conditions on NPP electrical components and the related protection of the components.

Component	Effects	Protection
Main generator	Negative sequence currents heat the rotor and can lead to damage of the generator if the unbalance situation remains for a too long time. There is also a risk of a pole slip.	• Negative sequence current relays with inverse time characteristics • Undervoltage protection • Pole slipping protection
Induction motor	If voltages are unbalanced, problems related to overheating and increasing vibrations can occur. A motor may also stall and it may not start-up with unbalanced voltages.	• Some critical motors have • negative sequence current protection • Some motors have undervoltage protection • Overload protection • Some motors have temperature measurements with alarms
Power electronics (converters)	Unbalanced voltages can cause synchronization difficulties for some power electronic devices. Undervoltage and/or voltage unbalance protection can be quite sensitive and devices can disconnect easily. Possibly connects automatically back when voltage normalized.	• Differential current protection • Ground fault protection
Transformers	Not considered as the most vulnerable component during open phase condition. Overheating can occur in some loading conditions.	• Differential current protection • Ground fault protection

3.3.3 Subsynchoronous oscillation

STUK (2019a) sets the general requirements for above mentioned disturbances among others in the following points:

"5408. Plant-specific frequency and voltage variations caused by an external grid, and those caused by electrical components or failures of the plant, shall be analysed.

5409. Frequency and voltage fluctuations analysed according to the requirement 5407 shall not endanger the safety functions during normal operation, anticipated operational occurrences or accidents.

5470. The electrical power systems shall be provided with reliable protection devices that, in the event of disturbances and failures, only deactivate the affected component or section of the electric power network (selectively) under any foreseen grid switching condition."

The literature review identified that the subsynchronous oscillations (SSO) are traditionally divided into two types of interactions depending on the types of devices participating in the interaction (IEEE 1992). 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 (Rosenström 2019, IEEE 1992, Rauhala 2014). A practical example of the importance to recognise the SSR was the first event occurred 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 (Walker et all 1975). 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 (Bongiorno 2011).

3.3.4 Loss of AC power

"According to Section 11(6) of STUK regulation STUK Y/1/2018, a nuclear power plant shall have off-site and on-site electrical power supply systems to cope with anticipated operational occurrences and accidents. It shall be possible to supply the electrical power needed for safety functions using either of the two electrical power supply systems."

Reliable offsite power is one key to minimizing the probability of severe accidents. Loss of offsite power (LOOP) can occur due to external events in the transmission grid. Li (2014) has observed significant differences in LOOP event description, category, duration, and applicability between the LOOP events used in NUREG/CR-6890 and the EPRI LOOP Reports. Also Different LOOP frequency calculation methods are used in NUREG/CR-6890 and in the EPRI's LOOP Reports. Biese (2018) studied possible frequencies of LOOP events due to external causes in the case of Fennovoima NPP in Hanhikivi. The study covered both the major part of the technical failures and disturbances mentioned in the previous sub-sections (1-phase fault, permanent failure, major national grid failure) as well as extreme weather (lightning, strong wind, tornados, downbursts, freezing rain, wildfires, extreme temperature and heavy rainfall), which have been accounted for. Also different mean times to repair (MTTR) have been assessed based on previous experiences on grid failures. The frequency of technical and lightning related failures for 400 kV power lines was assessed to be 2.88E-02/a and for 110 kV power lines substantially higher, 1.71E-01/a. The weather related 400 kV power line failure frequency was assessed to be 9.03E-03/a. Considering both 400 kV and 110 kV power lines, the frequency for a weather related power line failure was assessed to be 1.81E-02/a (Biese 2018). Kanerva (2004) analysed in his Master's Thesis the LOOP of Loviisa NPP and concluded that the frequency estimate is 3.33E-2 /a (once in 30 years) based on an extensive report on the vulnerability of the Nordic power system (Doorman et all 2004). Nordic and Baltic disturbance statitics of grid components are published annually and the latest reference is Fingrid 2019.

3.3.5 Operation of the switch-over automation

STUK (2019a) sets the general requirements for switch-over automation among others in the following points:

"*5402. The plant shall be provided with systems permitting power supply from the main generator to the plant systems in case the connection to the off-site grid is lost.*
5422. The plant shall be provided with a reliable switch-over automation to permit automatic switch-over between the off-site grid connections.
5423. The automatic switch-over between the plant's off-site grid connections shall be designed to ensure that any switch-over does not actuate the plant unit's safety systems designed to cope with postulated accidents."

The sudden drop of load, which means the opening the plant circuit breaker and switching over to the house load operation causes strong transients and stresses on several systems of the nuclear power plant. The voltage of generator busbar and the frequency of the power plant onsite grid immediately increase, when the plant circuit breaker is opened. Therefore, an important point in plant design and operation is to know the function of the components of the process systems in the electrical transient as the plant switches to self-use. Knowing these interactions will allow for better modelling of the plant and thus better control of the behaviour of the whole plant during the transient in transition to the house load operation. These interactions between process and electrical systems should also be made aware of plant upgrades and power upgrades to maintain the original level of safety. Otherwise, the original margin of safety may be unknowingly lost, thereby reducing the level of security (Hankivuo 2011).

If the switch-over automation works under normal operating conditions and no faults occur, the voltage of the generator busbar and safety classified busbars will typically increase by 15… 20% for a few cycles, after which it will return to the rated voltage. Similarly, the frequency of the plant rises typically from 3 to 4% (<52 Hz) for about a second, after which it drops to nominal, which may also mean a momentary underfrequency. A particularly strong transient results from undervoltage triggering, whereby the main generator generates a lot of reactive power and tends to support the grid, for example during short circuits. The examples of the last mentioned cases are the faults mentioned in sub-section 3.5 in Forsmark 1 2009 and Olkiluoto 1 2008 (Duchac and Noël 2011, Wämundson 2016 and OECD 2009).

3.3.6 Connections to the external grid

STUK (2019a) sets the general requirements for the connections to the external grid among others in the following points:

"5403. The off-site and on-site system for supplying power to the plant unit shall be designed to ensure that each of them has sufficient capacity to power the safety functions independently in accordance with the design criteria specified in Section 4.

5405. Cross-connections between the redundant parts of safety-classified electrical systems shall be avoided unless they are demonstrated to improve the safety of the nuclear facility.

5406. The cross-connections between the redundant parts of safety-classified electrical systems shall be designed to reliably prevent any unintentional coupling of the connections, and to make any human errors during commissioning and operation unlikely.

5417. Two independent connections to the external grid are required"

Hankivuo (2011) proposed so called "2/4 division model". Separated power supply for 2/4 divisions refers to a model in which two divisions are supplied by a 400 kV grid and a main generator, and the other two divisions are supplied by a 110 kV grid under normal operation. In exceptional circumstances, the inputs could be changed by a feed-in switching apparatus just as in the current implementation. In principle, this model would be possible with the current connection of existing plants in Finland, but the plants are not designed for such continuous use. Many of the disturbances transmitted from the main grid and the main generator could be better protected by this kind of connection model. In this model, the disturbances of the 400 kV network and the main generator affect only divisions 1 and 2, and the disturbances of the 110 kV network, respectively, affect divisions 3 and 4. This model would provide the desired diversity in power supply. However, it must remember that the 400 kV and 110 kV networks are not completely independent, but are interconnected via substations transformers. The advantage of this model is f.ex. that it mitigates the impacts of lightning surges. The disadvantage is that according to statistics, there are clearly more faults and disturbances in a 110 kV network than in a 400 kV network. However, it is unclear for the time being, how well this model would protect against network failures, and is one of the key recommendations for further research.

3.3.7 Flexible operation of NPP

STUK sets no special requirements for flexible operation of NPPs, which can be interpreted that flexible operation of NPP is normal operation state whether it will be applied in Finland in the future. However, some of the YVL requirements are closely linked to this issue in STUK 2019a:

"5223. The nuclear power plant shall be provided with reliable systems for monitoring and controlling the functioning of the reactor and the plant systems during normal operational states. Such systems are known as 'operational I&C systems'.

5224. The operational and limitation I&C shall maintain the process parameters within a range consistent with normal operation as well as monitor the condition of plant systems, structures and components.
5226. A nuclear power plant shall have limitation functions which, either automatically or with the assistance of operators, launch the corrective control and adjustment measures during anticipated operational occurrences (limitation I&C).
5307. According to Section 16(1) of STUK regulation STUK Y/1/2018, a nuclear facility shall contain equipment that provides information on the operational state of the facility and any deviations from normal operation.
5308. According to Section 16(3a) of STUK regulation STUK Y/1/2018, in order to control the nuclear power plant and enable operator actions, the nuclear power plant shall have a control room, in which the majority of the user interfaces required for the monitoring and control of the nuclear power plant are located. The scope of monitoring and control duties performed outside the control room shall be designed according to their feasibility."

ESSI (SAFIR 2018) project studied also the possible flexible operation in Finnish NPPs in the future preliminarily. The new units will be capable of flexible operation, but old units have only manual power controls possibility and new automation system would be needed for automatic control of load-following. Power system related studies of flexible operation in ESSI were limited on technical fault studies and speculations of risk. Areas of concern and risks for flexible operation are: thermal system & turbine, control room and personnel and financial profitability. It is expected that the disturbance sensitivity of the electrical components and ICT systems can increase. The load-following operation has some influence on the ageing of certain operational components and thus one can expect an increase in maintenance and surveillance (Hämäläinen & Suolanen 2019). STUK sees load-following as a technical issue and not as an issue that should be restricted by the law. The most obvious risk to system stability is that if large nuclear plant takes the major role in system balancing and plant disconnects from grid when there is low inertia in the grid (summer time). The project outlined also a risk analytic approach to assess options for flexible operation. The optimization of operational strategies of NPPs is both a multi-criteria task and an issue for multiple stakeholders. Just looking at from a single unit point of view is not sufficient, but it should be analysed from the portfolio of generating unit point of view. It is suggested that the assessment can be divided into three major categories: 1) grid system risks, 2) economical risks (of the plant owner), and 3) NPP reactor safety risks. These categories can be broken down into subcategories that can be assessed separately. This approach leads to a multi-attribute decision analysis framework, which also allows to take uncertainties into consideration (Pasonen 2018, and Holmberg 2018).

3.3.8 Electric systems in probabilistic risk assessment (PRA)

Nuclear power plant risk management covers the design, construction, commission, operating and decommissioning phases. Level 1 PRA determines accident sequences leading to nuclear fuel damage and estimates their probabilities. Level 2

PRA assesses the magnitude, probability and timing of a release of radioactive substances leaking from a nuclear power plant. Level 3 PRA, assesses the risk to people and the environment from a release of radioactive substances (STUKT 2019e). The main initiating event addressed to electric systems in PRA is the loss of external power (LOOP) and also in some countries the open phase conditions (B. Brück et al 2018). The almost similar event is the loss of internal grid, which may result from LOOP. The PRA consist of event tree and fault tree analyses. The fault tree describes the failure of a system or sub-system. In the fault tree analyses, more complex structures can be created by combining series, parallel, and -k / n coupled structures. The reliability calculation solves the minimum cut sets of the block diagram.

Faults simultaneously impairing multiple redundant trains of the electrical power supply system of NPPs have recently received growing attention by the nuclear community. This was triggered by events at several different NPPs including Byron in the U.S. or Forsmark in Sweden. Such events have generally not been included in PRAs of NPPs yet. The aim of COSI project is to study disturbances and faults using a comprehensive and in-depth analysis of events characterized by fault states of multiple trains of the electrical power supply system. Firstly, the possible causes of faults affecting multiple trains of the electrical power supply system and their consequences are assessed from an operating and modelling perspective. This deliverable includes the preliminary proposal of COSI safety case including some candidates for events need to be analysed further and which are important for need to reconsider safety design principles. During 2018, COSI started the development of a co-simulation model including the electrical power and thermo-hydraulic systems in order to investigate by simulation the impacts and the propagation of such faults. This work will provide inputs at the development of modelling and quantification methods to include them in PSAs.

COSI project provide inputs to different interacting efforts in PRA, but which are outside the scope of COSI project. The current PSA models of Finnish NPPs is possible to extend to allow for the modelling of the electric phenomena identified in the COSI simulation phase. This includes adding relevant equipment not modelled before and new failure modes of equipment already modelled. The additional reliability parameters and frequencies of initiating events required to quantify the extended PSA model need to be estimated. Finally, the additional failure mechanisms considered in the extended PSA model is possible to evaluate quantitatively.

4. Conclusions

This reports studies the safety assessment of electric systems for new operational modes. Experience from nuclear sector is that there is a continuous need to reconsider safety design principles. Term “safety case” is deliberately used here instead of safety analysis report to emphasize the safety demonstration aspect of the safety assessment. The work covers the definition of overall safety case for electric systems by investigating events, faults and disturbances related to electric systems.

The work bases on the literature review of the NPP electrical systems. The literature focuses on electrical system reliability, electrical disturbances and simulation of electrical systems. The literature survey 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 review and an analysis of these conditions, this report describes the current state of research on these topics. The literature review covers the role of electrical systems in an NPP and the design principles applied to them. Also the previous work done under the SAFIR programme during 2017-2017 and specific requirements related to NPP electrical systems are treated.

Based on the literature survey the safety case of electric systems in NPP for co-simulation is proposed. It covers the whole chain of electric systems enabling the structured approach for evaluation of possible common cause failures, faults, disturbances and design principles. These enables also evaluation the adequacy and balance of safety requirements including design philosophies, applied to the design of safety critical systems like redundancy, diversity, separation, fail-safety and automatic start.

The proposed safety case includes typical fault based studies of electrical systems like lightning overvoltages, short circuit, ground and open phase faults. Also other types of events are included in the safety case which are related to the safe operation of NPP like subsynchoronous oscillation, loss of AC power, operation of the switch-over automation, connections to the external grid and flexible operation of NPP. The aim is not to provide a complete compilation of possible events for the safety case related to electric systems, but to show important illustrative examples. Some of them will be selected later for the analyses by simulation using the COSI simulation platform. It will be of great value for COSI to investigate also disturbances that do not result in initiation of protection function in the electrical system.

The report covers also the role of electric systems in probabilistic risk assessment (PRA). The main initiating events addressed to electric systems in PRA are the loss of external power (LOOP) and also in some countries the open phase conditions. The almost similar event is the loss of internal grid, which may result from LOOP. Faults simultaneously impairing multiple redundant trains of the electrical power supply system of NPPs have recently received growing attention by the nuclear community. Such events have generally not been included in PRAs of NPPs yet. The preliminary proposal of COSI safety case includes some candidates of events for further investigation by simulation in order to analyse the impacts and the propagation in internal grid. This work will provide inputs at the development of modelling and quantification methods to include them in PRAs. The current PRA models of Finnish NPPs is possible to extend to allow for the modelling of the electric phenomena identified in the COSI simulation phase. This includes adding relevant equipment not modelled before and new failure modes of equipment already modelled. The additional reliability parameters and frequencies of initiating events required to quantify the extended PRA model need to be estimated. Finally, the additional failure mechanisms considered in the extended PRA model is possible to evaluate quantitatively.

Acknowledgements

This work has been mainly funded by VYR – the Finnish Nuclear Waste management Fund. Parts of this work has been funded also by Energiforsk (Sweden), Fingrid Oyj, Aalto University and VTT Ltd. The authors gratefully acknowledge the financial support from VYR, Energiforsk, Fingrid , Aalto University and VTT Ltd.

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Series title and number
VTT Technology 370

Title	**Safety case of electric systems in NPP for co-simulation**
Author(s)	Seppo Hänninen, Poria Divshali, Matti Lehtonen & Miro Rosenström
Abstract	This report studies the safety assessment of electric systems for nuclear power plants. Term "safety case" is deliberately used here instead of safety analysis report to emphasize the safety demonstration aspect of the safety assessment. The work covers the definition of overall safety case for electric systems by investigating faults and disturbances related to electric systems. The work bases on the literature review of the internal and external electrical systems of the nuclear power plant. The literature focuses on electrical system reliability, electrical disturbances and simulation of electrical systems. The literature survey 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 review and an analysis of these conditions, this report describes the current state of research on these topics. The proposed safety case includes typical fault based studies of electrical systems, like lightning overvoltages, short circuit, ground and open phase faults. Also other types of events are included in the safety case, which are related to the safe operation of the nuclear power plant like subsynchronous oscillation, loss of AC power, operation of the switch-over automation, connections to the external grid and flexible operation of the nuclear power plant. The aim is not to provide a complete compilation of possibleevents for the safety case related to electric systems, but to show important illustrative examples. Some of them will be selected later for the analyses by simulation using the COSI simulation platform. The report covers also the role of electric systems in probabilistic risk assessment (PRA). The main initiating events connected electric systems in PRA are the loss of external power (LOOP) and also in some countries the open phase conditions (open phase condition).
ISBN, ISSN, URN	ISBN 978-951-38-8727-8 ISSN-L 2242-1211 ISSN 2242-122X (Online) DOI: 10.32040/2242-122X.2020.T370
Date	February 2020
Language	English
Pages	44 p.
Name of the project	Co-simulation model for safety and security of electric systems in flexible environment of NPP
Commissioned by	
Keywords	Nuclear safty, electrical systems, simulation
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111, https://www.vttresearch.com

Safety case of electric systems in NPP for co-simulation

Electrical systems perform several functions in a nuclear power plant.These functions include generation and transmission of electrical power, distribution of power to processes and control systems, and operation of various safety systems. As almost every feature in the nuclear power plant 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.
This report studies the safety assessment of electric systems for nuclear power plants. Term "safety case" is deliberately used here instead of safety analysis report to emphasize the safety demonstration aspect of the safety assessment. The work covers the definition of overall safety case for electric systems by investigating faults and disturbances related to electric systems. The proposed safety case includes typical fault based studies of electrical systems, like lightning overvoltages, short circuit, ground and open phase faults. Also other types of events are included in the safety case, which are related to the safe operation of the nuclear power plant like subsynchronous oscillation, loss of alternative current power, operation of the switch-over automation, connections to the external grid and flexible operation of the nuclear power plant. The aim is not to provide a complete compilation of possible events for the safety case related to electric systems, but to show important illustrative examples. Some of them will be selected later for the analyses by simulation using the COSI simulation platform.

ISBN 978-951-38-8727-8
ISSN-L 2242-1211
ISSN 2242-122X (Online)
DOI: 10.32040/2242-122X.2020.T370

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