

OPERATIONAL EVENTS IN OFF-SITE POWER SYSTEM

REPORT 2016:323



GRID INTERFERENCE ON
NUCLEAR POWER PLANT
OPERATION



Operational Events in Off-Site Power System

Nuclear power plant Experiences and Mitigating Actions

MIKAEL WÄMUNDSON

ISBN 978-91-7673-323-3 | © 2016 ENERGIFORSK

Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Coverpicture: TVO

Foreword

This project was performed to gather information on relevant disturbances, and following mitigating actions taken in Swedish and Finnish nuclear power plants to prevent these kinds of disturbances from occurring again. The mitigating actions are summarized to form a toolbox of actions that can be retrofitted in an existing plant.

The study was carried out by Mikael Wämundson, Daniel Karlsson and Sture Lindahl, senior consultants at DNV GL. This project is part of the Grid Interference on Nuclear power plant Operations, GINO program, financed by Vattenfall, Uniper, TVO, Fortum, Skellefteå Kraft, Karlstad Energi and the Swedish Radiation Safety Authority.

Reported here are the results and conclusions from a project in a research program run by Energiforsk. The author / authors are responsible for the content and publication which does not mean that Energiforsk has taken a position.

Sammanfattning

Den här rapporten presenterar ett antal internationella händelser där fel i elkraftssystemet kring kärnkraftsanläggningar har haft påverkan på anläggningarnas interna kraftsystem och rent av riskerat strålsäkerheten. Vidare presenteras erfarenheter från de nordiska kärnkraftverken och vilka åtgärder man där vidtagit för att förhindra att fel i yttre nät får allvarliga konsekvenser för anläggningssäkerheten.

Fyra olika verktyg för att ytterligare förhindra framtida incidenter och öka immuniteten hos kärnkraftsanläggningarnas interna kraftförsörjning presenteras.

Det första verktyget är en metod för att detektera fasobalans, och presenteras då detta fenomen aktualiserades av händelsen i Forsmark den 30 maj 2013. Den presenterade metoden implementeras i redan tillgängliga numeriska reläskydd för aggregat- och starttransformatorer.

Det andra verktyget fokuserar på att aggregatet ska behålla sin koppling till yttre nät i händelse av närbelägna fel i nätet i kombination med felfungerande felbortkopplingssystem (brytare). Genom att minimera felbortkopplingstiden ökar möjligheten för aggregatet att vara synkront kopplat till nätet. Verktyget som presenteras är seriekopplade dubbla brytare.

Det tredje och fjärde verktyget syftar inte till specifika tekniska problem utan är på högre abstraktionsnivå. Koncepten som presenteras är "withstand or isolate" och metoden att duplicera analyser.

Summary

This report presents a few international events where disturbances in the off-site power system have had impact on the on-site power system and jeopardized the nuclear safety of the plant. A number of experiences from four Nordic NPPs are presented together with the mitigating actions taken to prevent further serious events.

Four possible “tools” are presented in the report that could be further investigated and applied to minimize future incidents and events related to loss of off-site power.

The first tool is a method to detect loss-of-phase, which is presented since this phenomenon was accentuated by the event in Forsmark on May 30, 2013. The method presented utilizes existing IEDs for step-up and start-up transformers.

The second tool addresses the issue of keeping the nuclear units connected to the grid in case of close-up faults in the network in combination with a non-functioning fault-clearing system (circuit-breaker). By reducing the fault-clearing time the ability for the NPP to stay synchronized to the grid is increased. The tool presented is double circuit-breakers in series.

The third and fourth tools do not address specific technical problems but are higher level concepts to prevent future incidents and possible events of station blackout. The tools are the concept of “withstand or isolate” and duplicated analyses.

List of content

1	Introduction	10
1.1	Some frequently used abbreviations and terms	10
1.2	Background	11
1.3	Scope	12
1.4	Meetings	12
1.5	Outline of the report	12
2	International Experiences from NPPs	13
2.1	The European Clearinghouse	13
2.1.1	IAEA IRS database - Event IRS 6256 - Disconnection of all four units from grid at Dukovany, 1990	14
2.1.2	IAEA IRS database - Event IRS 7859 - Complete loss of off-site power at Chasnupp, Pakistan, 2006	14
2.1.3	2001 Maanshan (Taiwan)	15
2.1.4	1993 Kola Event (Russia)	16
2.2	NUREG Reports	17
2.2.1	Operating Experience Assessment – Effects of Grid Events on Nuclear Power Plant Performance	17
2.2.2	Susceptibility of Nuclear Stations of External Faults	17
2.2.3	Conclusions from the reports	17
2.3	Summary of literature survey	18
3	Experiences from Four Nordic NPPs	20
3.1	Forsmark	20
3.1.1	Mitigating actions taken at Forsmark	22
3.2	Ringhals	23
3.2.1	Mitigating actions taken at Ringhals	24
3.3	Oskarshamn	24
3.3.1	Mitigating actions taken at Oskarshamn	27
3.4	Olkiluoto	30
3.4.1	Mitigating actions taken at Olkiluoto	31
4	Toolbox of Possible Mitigating Actions	33
4.1	Detection of Loss-of-Phase	33
4.2	Double Breakers, in Series	34
4.2.1	Comparison for different failure modes	35
4.2.2	Possibilities to retrofit	36
4.3	Duplicated Analyses and avoiding common-cause errors	37
4.4	Concept of “Withstand or Isolate”	38
4.4.1	How to obtain the immunity level	39
4.4.2	The importance of the protection system	40
4.4.3	Uphold sufficient level of isolation	40

	4.4.4 Example from the Industry	40
5	Conclusion and Future Work	42
	5.1 Future work	43
6	References	44

1 Introduction

1.1 SOME FREQUENTLY USED ABBREVIATIONS AND TERMS

BWR: Boiling Water Reactor

PWR: Pressurized Water Reactor

EDG: Emergency Diesel Generator

I&C: Instrumentation and Control

LER: Licensee Event Report

LOOP: Loss Of Off-site Power

NPP: Nuclear Power Plant

SBO: Station Black Out

IED: Intelligent Electronic Device

This report has gathered information from various international reports and texts. Some expressions and the exact meaning of the expressions, related to the nuclear power industry, vary depending on location. The text in this report is using the expressions in the referred source.

On-site and off-site power system

According to IAEA [11] “the on-site power systems and off-site power systems work together to provide necessary power in all plant conditions so that the plant can be maintained in a safe state. Off-site power systems are not plant equipment. They are, nevertheless, essential to the safety of a nuclear power plant, and they are important in the defense in depth concept.” The relationship is illustrated in figure 1.1.

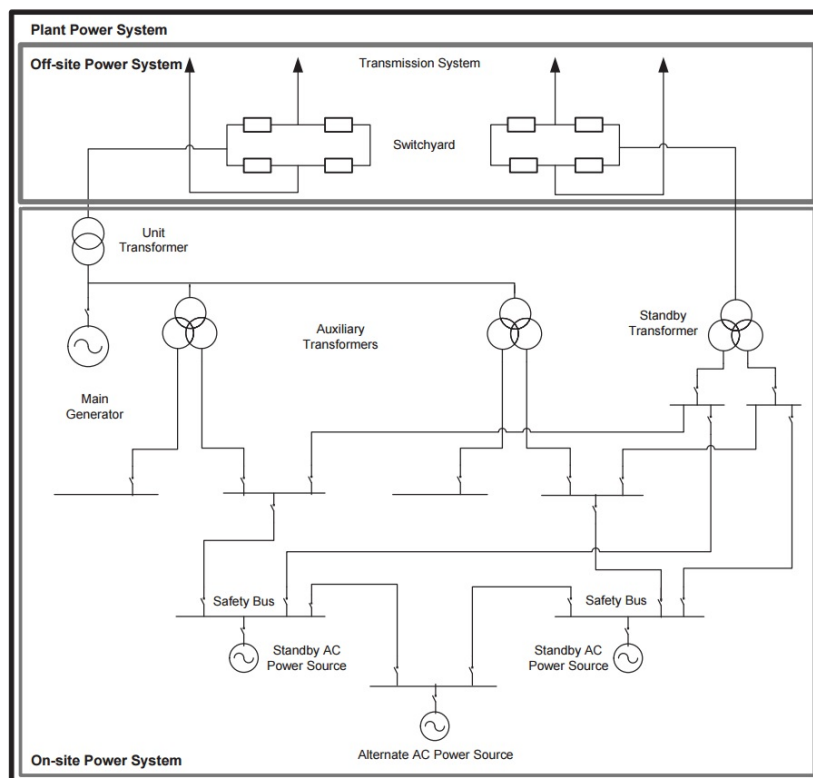


Figure 1.1. Relationship of the plant electrical power system, the off-site electrical power system and the on-site electrical power system for a nuclear power plant. [11]

1.2 BACKGROUND

In the Energiforsk report *Grid interference on operations, Mapping of R&D needs* [1] a number of topics for future work were identified;

- Survey of operational events from the off-site power system with focus on retrofit of mitigating actions
- Subsynchronous resonance phenomenon and modelling combined with hybrid simulations (simulations using different tools in parallel and/or by several parties)
- Survey on new electrical devices with different technology compared to existing electrical devices
- Survey of methodologies to verify that the outer grounding line network in the nuclear power plants is intact
- Generic lightning model of the Nordic nuclear power plants to study lightning incidents due to conducting

This report is the outcome of the first of these identified topics. The report [1] further states the scope of this survey as:

“The aim of this investigation is to provide power plants with information of relevant disturbances that is needed to handle and to support the actors involved in the decision process with a toolbox of mitigating actions. The toolbox will handle the impact of disturbances and also the possibility how to reduce the exposure. The mitigating actions should also be suitable for retrofitting in an existing plant.

The first phase of the project is to summarize events that have occurred around the world with some emphasis on events in Sweden and Finland. Previous work in this

area such as DIDEYSYS and ROBESYS should be utilized in order to make this phase more efficient. After collecting the data, an assessment of the most relevant types of disturbances should be performed and impact on vital equipment in the plants should be compiled.

The second phase of the project is to assemble mitigating measures that have been retrofitted into existing plants. Examples of such mitigating measures could be adjustment or modification of relay protection, but it could also include more ambitious countermeasures such as new sources of electrical power supply or insulating devices such as motor generator sets or power electronic devices etc.”

Further on, [1] states that the final report should include:

- Description of relevant disturbances
- Root cause for the disturbances
- Impact of the disturbance
- Lessons learned and implementation of mitigating measures

1.3 SCOPE

The scope of the project has been a bit refined compared to the goals set up in [1]. Some keywords/phrases were identified during project meetings in the steering group;

- Withstand or isolate
This is a concept that was discussed at the project meetings and should be considered in the report
- Toolbox of mitigating actions
More focus in the report should be on the mitigating actions taken or suggested than on events
- “We are blind, it is all there, but we cannot see it...”
This has been a dilemma in the studies; how to foresee vulnerabilities in the systems and for what situations actions have to be taken
- Short and new preferred over long and old
Keep the report short and with relevant information

1.4 MEETINGS

During the project, two meetings have been held; one start-up meeting on November 12, 2015 and one mid-way meeting on February 18, 2016. The meetings were intended to keep the project in line with the intentions of the reference group, by setting ambition levels, scope, etc.

1.5 OUTLINE OF THE REPORT

The content in this report is outlined as follows. Chapter 2 presents the result from a literature survey on international experiences at nuclear power plants (NPPs) regarding station blackouts, or near station blackouts, triggered by loss of off-site power. The experiences are mainly from different databases on the subject. Chapter 3 gives a little more detailed overview of experiences from the four Nordic NPPs Forsmark, Ringhals, Oskarshamn and Olkiluoto together with the mitigating actions performed as consequences from these events. Chapter 4 summarizes a collection of tools to minimize the probability for future station blackouts triggered by loss of off-site power. Chapter 5 finally, concludes the report and gives directions for future work.

2 International Experiences from NPPs

This chapter summarizes conclusions from two of the more comprehensive sources found related to loss of off-site power and station blackout at NPPs, with an international focus;

- The European Clearinghouse on Operational Experience Feedback for Nuclear Power Plants, and
- NUREG Reports from the U.S. Nuclear Regulatory Commission (NRC)

The lessons learned from these events and mitigating actions taken are to be considered in relation to the conditions at the affected power station.

2.1 THE EUROPEAN CLEARINGHOUSE

The European Clearinghouse on Operational Experience Feedback for Nuclear Power Plants was established by European Nuclear Regulators for enhanced collaboration on Operational Experience Feedback (OEF) and dissemination of the lessons learned from NPP OEF and promotion of advanced event assessment approaches and methods. In a recent study within Clearinghouse an in-depth analysis of events related to loss of off-site power (LOOP)¹, station blackout (SBO) and near SBO has been conducted. [12]

The scope of the study was to screen four databases over approximately the past 20 years to identify LOOP and SBO related events;

- Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
228 events were selected
- Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS)
190 events were selected
- U.S. NRC Licensee Event Reports (LER)
119 events were selected
- IAEA International Reporting System (IRS)
52 events were selected

The almost 600 international events were further analyzed in depth for the direct causes, root causes, contributing factors, consequences and lessons learned and to classify the events into groups in order to establish the main conclusions on the topic.

From the above list of events a number of events were selected as “representative” due to interesting correcting actions or lessons learned, and their real or potential impact on the NPP safety. Four of the analyzed events are of interest in this report:

- IAEA IRS database - Event IRS 6256 - Disconnection of all four units from grid
- IAEA IRS database - Event IRS 7859 - Complete loss of off-site power
- 2001 Maanshan (Taiwan)
- 1993 Kola Event (Russia)

¹ A number of different types of events are considered in the screening related to LOOP; partial loss of external power, total loss of external power, loss of power supply, physical loss of electrical bus-bars and loss of bus-bar power supply caused by plant related events.

2.1.1 IAEA IRS database - Event IRS 6256 - Disconnection of all four units from grid at Dukovany, 1990

A short circuit occurred in an external 400 kV switching station due to an error by an electrician. It resulted in a disconnection of both 400 kV and 110 kV lines to all four units of the NPP. The 110 kV lines for backup power of the plant lost their supply from the 400 kV system due to loss of the 400/110 kV transformer. A total loss of the 100 kV system followed as a connected thermal power station tripped due to overloading. Unit 1 failed to cope with the load rejection due to false actuations of distant protections at its generators, and it resulted in a loss of off-site power with fast reactor scram due to the loss of all MCPs (Main Cooling Pump). The other units coped with the load rejection.

Notable amongst the root causes of the event are:

- a failure of an electrician in the external switching station in the course of a test of a disconnecting switch in an output line of the Unit 3 shut down for refuelling, violating procedures;
- recurrent problems with turbine fast acting stop valves, with generator circuit breakers, and with diesel generators;
- improper connection of the output lines of all four units into a common bus-bar at the external switching station and insufficient backup power supply sources from the grid.

In evaluation of the event some lessons can be learned, according to the Clearinghouse study:

- Modifications of components, such as generator circuit breakers and diesel generators, are necessary in order to increase their reliability;
- The information system for control room personnel should be enhanced (personnel were distracted by unnecessary actions) as well as the automatic control circuits of condensate pumps and several valves;
- Unit disconnection from grid should be tested regularly in the course of start-ups following refuelling;
- Operators should be trained in the course of complex transients with multiple occurrences.

2.1.2 IAEA IRS database - Event IRS 7859 - Complete loss of off-site power at Chasnupp, Pakistan, 2006

Due to a major fault on the national grid, the two off-site power lines, 220 kV and 132 kV respectively, were lost resulting in unavailability of the two off-site power sources. Although, the plant has the provision of house-load operation during loss of off-site power, reactor coolant pumps tripped on bus under frequency resulting in unavailability of power for forced cooling of the plant. There are two emergency diesel generators which are meant to ensure availability of two independent on-site emergency power sources at plant, with each one dedicated for one emergency bus. The two diesel generators remained in operation until the restoration of off-site power; however, room ventilation fan for one of the emergency diesel generators together with the fuel transfer pump of the same diesel generator failed to start.

In evaluation of the event some lessons can be learned:

- With the coincidence loss of power from off-site sources and the main generator, the page/party communication system became unavailable as it draws power from normal buses and is not provided with dedicated UPS, however, normal telephone lines from plant exchange remained available for communication between main control room and local control areas. This created inconvenience to complete certain important actions such as resetting of some breakers. Therefore, improvement in communication means with the personnel in field during such events is needed.
- Plant alarm system for declaring/displaying the alert alarms for escape/evacuation became unavailable on loss of off-site power.
- This was the worst power breakdown in the life of the plant, up till now, which resulted in loss of both off-site powers sources as well as provision of auxiliary functions to the emergency diesel generators. Therefore, the plant needs to adopt a strategy to strengthen measures in case of such a situation in the future.
- Further improvement in the reliability of emergency diesel generators by investigating unavailability of the ventilation system and the fuel transfer pump of one of the diesel generators, experienced during the event.

2.1.3 2001 Maanshan (Taiwan)

The description of the event and lessons learned are based on NUREG report [6].

During spring season in Taiwan, salty wind from the ocean can degrade the insulation of power transmission lines and cause the instability of off-site power in nearby nuclear power station. On March 17, 2001, 3:23 am, 345 kV off-site power line was lost due to seasonal salty wind and 161 kV off-site power remained available. Unit 1 reactor tripped and was maintained at hot standby condition by operators.

At 0:46 am, March 18th, a malfunctioning breaker in on-site AC power electric system accidentally grounded, which produced an electric arc that damaged other electric systems. Emergency 4.16 kV bus train A and B both lost power supply which is a station blackout situation. At 2:54 am, the emergency diesel generator successfully supplied AC power to emergency 4.16 kV bus B, SBO situation was terminated, with a duration of about 2 hours.

In [10] some more information on the event is given:

“The fire started as the result of a fault in the safety-related 4.16 kV switchgear supply circuit-breaker. The initial fault caused explosions, arcing, smoke, and ionized gases which propagated to adjacent safety-related 4.16 kV switchgear and damaged six switchgear compartments. The damage resulted in complete loss of the faulted safety bus and its emergency diesel generator (EDG) and loss of offsite power (LOOP) to the undamaged safety bus due to faulting of its off-site electrical feeder circuit. An independent failure of the redundant EDG resulted in loss of all AC power. Smoke hindered access to equipment, delaying the investigation and repair of the failures. The SBO was terminated after about two hours when an alternate ac (AAC) EDG was started and connected to the undamaged safety bus.”

When facing beyond design basis accidents, great uncertainties are associated with regular plant systems and components. Therefore, a strategy that can bring the plant back to safe conditions as soon as possible should be considered. Performing steam

generator controlled-depressurization at the early stage of the accident and, if no regular coolant injection system is available, line up the alternate injection system in 3.5 hours after SBO could keep the fuels covered with water. In addition, after plant is under control at the early stage of the accident, on-site operators should recover AC power as quickly as possible.

2.1.4 1993 Kola Event (Russia)

Due to the hurricane wind the "Kolenergo" grid system collapsed, and the 330 kV, 154 kV, and 110 kV high voltage transmission lines were damaged. Voltage transients in the NPP unit auxiliary power line resulted in trips of the turbine generators and other main equipment and reactor scrams.

An attempt to supply power to Units 1 and 2 equipment by emergency connections from diesel generators (DGs) was unsuccessful due to DG failure for the following reasons: deficiencies in DG control design configuration and deficiencies of work planning and organisation by NPP management as regards timely changes of DG control design configuration and ensuring emergency power supply to essential equipment.

Safety systems at Units 3 and 4 are configured as three channels with independent power supplies, service water supplies, compressed air supplies, etc. For this reason total LOOP conditions at Units 3 and 4 passed without serious criticism.

The main causes for the sequence of events that took place in Kola NPP Units 1 and 2 are:

- High wind speeds, 40 m/s, and multiple failures of electrical grid components with load shedding. Voltage and frequency oscillations - poor quality of electricity in the power system
- Several design deficiencies in the automatic control of emergency diesel generators
- Deficiencies in personnel training and procedural deficiencies
- Maintenance deficiency of DG emergency protection elements
- Operational failure of the computer complex due to loss of voltage on its supply feeders
- Lack of uninterruptible power supply for vital 380 V consumers at Units 1 and 2 standby diesel station

The following is needed to prevent the recurrence of a similar event:

- Develop a project and perform back fitting of vital and essential power systems including safety system trains to bring them in line with the modern safety requirements
- Perform the assessment of the total loss of unit power events and of unit stability in conditions of power system accidents with extended frequency and voltage oscillations and envisage appropriate corrective actions (including automatic changeover set points, protections and interlock settings and personnel actions) to assure specified cooldown and allocate one of the units for operating to meet the in-house power requirements
- Perform assessment of operational documents, of emergency procedures and programs of personnel training with the aim of elaborating and expanding personnel actions during the blackout events. After these documents updating conduct personnel training and emergency exercises /training sessions

2.2 NUREG REPORTS

Two NUREG reports published by NRC (from NUClear REGulatory Commission, NRC) are of special interest for this study

- “Operating Experience Assessment – Effects of Grid Events on Nuclear Power Plant Performance”, published December 2003. [8]
- “Susceptibility of Nuclear Stations of External Faults”, published September 2014. [9]

2.2.1 Operating Experience Assessment – Effects of Grid Events on Nuclear Power Plant Performance

The main scope for this NUREG report is

- Experiences and assessments are presented based on how external grid events have affected different NPPs.
- The events occurred mostly between the years of 1994 and 2001.
- The main objective of the study was to gather information that “[...] provides a baseline of grid performance to gauge the impact of deregulation and changes in grid operation.”

2.2.2 Susceptibility of Nuclear Stations of External Faults

The main scope for this NUREG report can be summarized as

- “[...] identify the electrical system vulnerabilities that contribute to electrical fault propagation into the nuclear plant’s switchyard.”
- As a part of this, several external grid events that had significantly affected NPPs were analyzed.
- The events took place between the years of 2003 and 2008.

2.2.3 Conclusions from the reports

From these two reports, and the events described in them, the following conclusions and recommendations can be listed

- “Many of the LOOPs and plant trips [...] would otherwise have been avoided if the *existing properly-designed protection systems had operated as originally intended.*”
- “In some cases it may be possible to *reduce the time delays for backup protection or breaker failure schemes* to reduce or mitigate the effects of electrical transient events [...] By minimizing the magnitude and duration of a disturbance at the NPP switchyard, it may even be possible to *allow the plant to remain on line, or ‘ride through,’* some disturbances to maintain the beneficial voltage and VAR support the nuclear plant generator is supplying to the grid, thereby contributing to the overall stability of the transmission system.”
- Frequent current unbalances affecting the equipment
“Experience indicated that transmission system operation or disturbances may cause sustained or frequent current unbalances that result in damage to electrical equipment. It is common practice to protect expensive or important non-safety equipment from current unbalances. Safety equipment should also have the same level of protection.”
- Transients affecting the scram capability of the reactor
“Grid-induced reactor transients can effect scram capability. Operating experience

identified an instance where an anticipated transient without scram mitigation based on end-of-cycle recirculation pump trip logic failed to operate correctly during a transmission system fault that produced large electrical load fluctuations.”

- Consequences regarding over-frequency conditions and improper protective relay settings
“Grid conditions which result in over-frequency conditions can have unexpected consequences. At one plant, over-frequency conditions following a load rejection caused speed-up of the reactor coolant pumps which increased flows that generated forces to within a small margin of those causing uplift of the fuel rods. The over-frequency condition was not properly accounted for by the plant protective relay control logic.”
- Implementation of telecommunications – based relaying
“The high speed, sensitivity, and reliability of telecommunications-based relaying in backup protection helps to minimize the effects of primary protection failures.”
- Increasing the reliability in critical parts of the system
“Reliability in switchyards incorporating the breaker-and-a-half bus arrangement could be improved for the most critical transmission circuits and the main generator connection by modifying the circuit breaker arrangement for those connections to a full double-bus, double-breaker arrangement.”
- Increasing the redundancy in the protection system
“Improving the reliability of primary protection of the NPP switchyard protection systems can help them cope with the fault more effectively. This can be achieved by using redundant protective equipment such as dual relays, circuit-breakers, and telecommunication channels.”
- Identify crucial and significant components
“Conducting grid transient analyses to identify those relays and contacts that can have a significant impact on conditions at the NPP switchyard buses may provide valuable insights when reviewing and/or updating the protection schemes at or near the NPP switchyard.”
- Inspection, testing and maintenance of protection system and equipment
“[...] protection systems and equipment in selected nearby switchyards, transmission lines, substations, and large generating units (that have been shown by analysis to have a significant impact on nearby NPPs), may be subjected to a more frequent and augmented level of inspection, testing, and preventive maintenance.”
- Develop new industry standards
“Combined efforts from the NRC, FERC/NERC, the nuclear industry, and affected transmission system operators could lead to the development of industrywide standards for:
 - × the interface between NPPs and the transmission (or sub transmission) networks,
 - × the electrical protection schemes for the interface, and
 - × the maintenance of the primary and secondary protection equipment at the interface”.

2.3 SUMMARY OF LITERATURE SURVEY

A lot of references are available related to the subject of operational events in the off-site power system of nuclear power plants, and extensive projects have been performed such as DIDEYSYS and ROBESYS. For this survey it was found that the screening of

databases presented by Clearinghouse together with analyses and conclusions in NUREG reports where accessible ways to find data.

Even if a lot of events are found in databases, not many have been relevant for the scope of this report. However, four events are presented in some more detail and the main “lessons learned” from these events could be summarized as:

- The reliability of critical on-site equipment must be ensured
- Training of personnel to handle situations of loss of off-site power is important
- Perform testing to ensure proper function of equipment and procedures
- Assess (by simulations and experienced events) the immunity of the plant towards events in the off-site power system

3 Experiences from Four Nordic NPPs

In this section experiences from the four Nordic NPPs Forsmark, Ringhals, Oskarshamn and Olkiluoto of events due to problems in the off-site power system, or in some case the main generator, are listed together with mitigating actions that have been taken as a result of the events. In Finland is also situated the Loviisa nuclear power plant. No events from the two units at Loviisa have been selected in the screening of experiences in this report.

3.1 FORSMARK

Forsmark nuclear power station is situated on the East coast of Sweden, North of Stockholm. It consists of three units, Forsmark 1, 2 and 3; all BWRs. All units are primarily connected to the 400 kV transmission network, Unit 1 radially connected to Tuna, Unit 2 radially connected to Odensala, whereas Unit 3 is a meshed connection point in the network. The secondary infeed is the 70 kV network where a gas turbine is also available as backup power. In figure 3.1 a simplified diagram of the off-site power supply to Forsmark is shown.

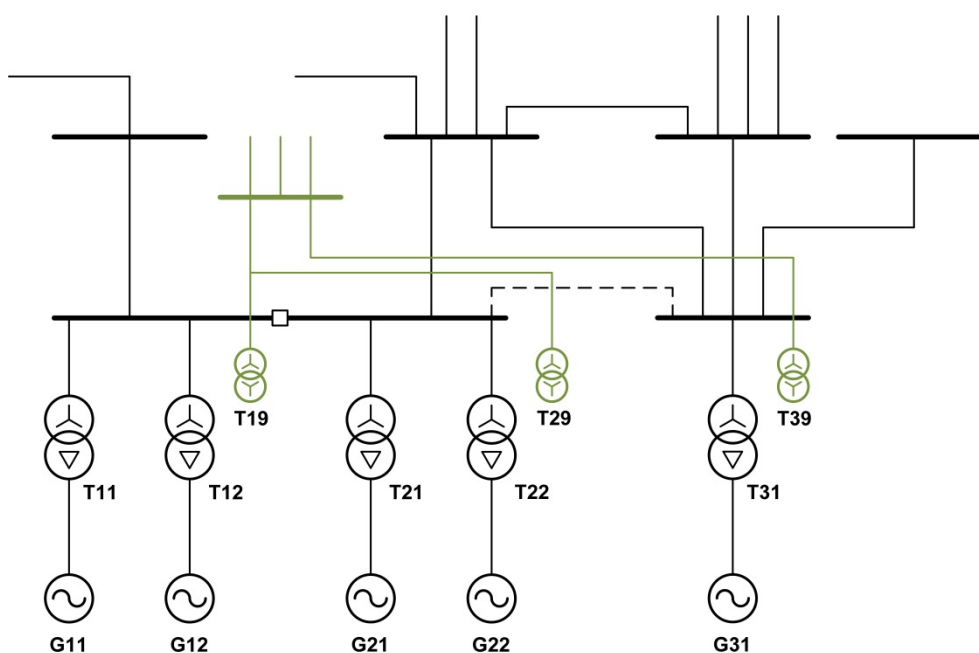


Figure 3.1. Simplified diagram of 70 kV (green) and 400 kV network connections of Forsmark.

The incidents that have occurred in Forsmark, particularly the events on July 25, 2006 and May 30, 2013 have put focus on the vulnerability of the off-site and on-site power systems.

When designing the facilities, considerable effort was put in the electrical separation of subdivisions. However, the electric equipment in the different subdivisions is not functionally separated during normal operation. Logic circuitry and protection systems have been designed to assess if off-site electric power is available or not. The protection

system for the safety bus-bars is using the positive-sequence values for the voltages. The safety bus-bars are isolated if the voltage is below 65% for more than one second.

Following is a list of events at Forsmark that have been notable.

July 25, 2006

During switching operations in the 400 kV substation FT46 (substation for Forsmark 1 and 2) on July 25, 2006 a short-circuit occurred and the unit circuit-breakers to Forsmark 1 were tripped. The low voltage during the short-circuit caused an increase of the generator excitation. When the unit circuit-breaker had tripped the voltage increased and the fast increase caused both the rectifier and inverter (system 655) to trip leaving two battery-secured subdivisions without power.

The unit went into house-load operation with a following turbine trip. As the frequency decreased the generator under-frequency protection did not trip the generator breaker at 47.5 Hz, due to wrong connections of the protection (the installed protection system was dependent on a correct phase sequence, when the plant was built two phases were crossed). Instead the diesel-backed network was isolated by tripping of circuit-breakers at 47 Hz.

The loss of voltage in the diesel-backed network resulted in starting of the diesel generators, due to under-voltage. However, since two subdivisions had lost the uninterruptable power supply, the startup of the corresponding diesel generators was canceled, since the tachometer was powered by the uninterruptable power supply.

When the generator circuit-breaker had tripped a manual transfer was initiated to the 70 kV network and the startup transformers for all four subdivisions.

The incident at Forsmark 1 showed how the function of the diesel generator was jeopardized due to the dynamic behavior of the event. It is noteworthy that the absolute value of the voltage was not the issue; it was the quick variation—first decreasing, then increasing—together with the design of the rectifier control system that caused the over-voltage and the disconnection of the inverter.

June 13, 2008

On June 13, 2008 the 400 kV line between Tuna and Hagby was hit by lightning. At the time Forsmark 1 was not in service but Forsmark 2 was connected to the 400 kV system. The diesel-backed system of Forsmark 2 was not affected, but the 649 system (frequency converters for the main circulation pumps) did not function as intended due to several faults in the control of the inverter (the system was unable to correctly measure the voltage phase angles). Similar to the incident on July 25, 2006 at Forsmark 1, the rectifier did not withstand the variations in the voltage during the event. During design of the system such variations in the voltage were not considered.

July 13, 2012

On July 13, 2012 an inverter in the 677 system (battery secured ac system) at Forsmark 3 (yearly outage) tripped during a lightning storm. Probably, it was over-voltage transients emanating from the off-site power system that caused damages to the thyristor switches in the static switch. During the event the unit was connected to the 70 kV network, which is considered more vulnerable to lightning than the 400 kV network, due to the lack of overhead ground wire and surge arresters. It is worth

noting that only one subdivision endured without damage to any thyristor switch, and that subdivision was in island operation during the event. Thyristors in other subdivision, that were energized but unloaded were damaged.

The disturbance represents a type of events that is challenging due to the fast transient behavior of the voltage.

May 30, 2013

During a test of the excitation system for the Forsmark 3 generator during outage on May 30, 2013, an undeliberate trip signal was sent to the unit circuit-breaker. However, only two out of three poles in the circuit-breaker were opened, resulting in an unbalanced supply voltage. The relay protection system for the diesel-backed system did not function on under-voltage since positive-sequence voltage was above 65%. There was no presentation in the control room for the voltage unbalance since they were based on the same phase-to-phase voltage for all subdivisions.

The voltage unbalance was detected by an experienced operator who *heard* it. By manual operation the diesel-backed power system was isolated.

The incident at Forsmark 3 on May 30, 2013 showed the risk of unsymmetrical voltage putting objects on the secured busses out of action. This risk can be decreased considerably by introducing a protection system that measures the voltage and isolates the safety bus-bars from the off-site power system in case of unsymmetrical voltage harmful to the equipment.

During the event the 70 kV power system was not available due to the reconstruction of the station ÄT66. It was unfortunate that simultaneous maintenance were performed on the 400 kV station and at the same time test of the generator excitation system (which may trip the 400 kV circuit breakers).

One experience from historical incidents is how often power electronic components are involved, often in different applications.

3.1.1 Mitigating actions taken at Forsmark

As direct actions to the incident at Forsmark 1 on July 25, 2006 an action list, the so-called "60-point list" was prepared and executed, which in part included:

- Wiring to the generator relay protection was corrected as to measure positive sequence quantities
- Selectivity between rectifier and inverter in 655 system was assured
- Fast overvoltage protection after rectifier in system 655 installed
- Dependence in battery-supplied power to start the diesel sequence was eliminated by transferring critical control functions to dc power system
- Duplicated power supply to critical equipment in the control room
- Over- and under-voltage relay protection for the generator bus was modified
- Electric equipment (mostly rectifiers) have been analyzed and tested regarding immunity to voltage transients

Following the events at Forsmark 3 in 2012 and 2013 additional actions have been initiated:

- Protection for unbalance voltage is being installed
- The lightning protection system is being improved

3.2 RINGHALS

Ringhals nuclear power station is situated on the West coast of Sweden with four units, Ringhals 1, 2, 3 and 4. Unit 1 is a BWR whereas the other units are PWRs. All units are connected radially to the 400 kV transmission network, with Strömme and Horred being the first meshed stations. The secondary infeed of power is from the 130 kV network where also a gas turbine is available as backup. The 400 kV and 130 kV connections are placed in the same switchyard some hundred meters from the units. A system transformer interconnects the two voltage levels at the connection point of Ringhals 3. In figure 3.2 a simplified diagram of the off-site power system is shown.

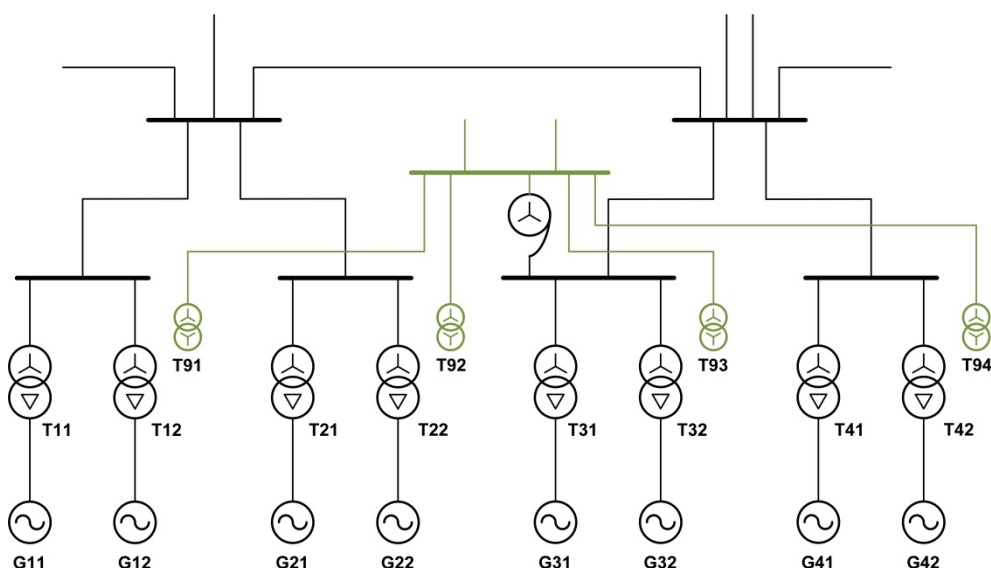


Figure 3.2. Simplified diagram of 130 kV (green) and 400 kV network connections of Ringhals.

Notable event at Ringhals:

July, 2008

During re-fueling on the night between July 31 and August 1 the so-called Balduf equipment (used for cleaning of the cavity water) indicated failure and tripped due to unbalanced voltages. The equipment is fed from the start-up transformer T93, connected to the 130 kV network. An analysis indicated a phase difference of 10 V on the 230 V system. Further analysis showed that the cause was a non-functioning breaker pole for the transformer bay in the 130 kV station.

The event led to further investigations on the possibilities to detect unbalanced voltages at the plant.

3.2.1 Mitigating actions taken at Ringhals

Here follows a selection of actions taken prior to the event in Forsmark 2006:

- Main generator
Installation of under-frequency protection
- Main generator
Modified set-values, under-voltage protection (a number of levels, delays and reset values to identify potential out-of-step conditions)
- Step-up transformer
Modified set-values, high impedance earth fault protection (NIS2 inverse time)
- Block differential protection
Main generator excluded from the zone of protection
- Longer insulator stacks (to cope with environmental conditions)
- Power supply to I&C for steam-driven pumps, from containment filtered ventilated mobile equipment

A selection of actions taken after the Forsmark event in 2006:

- Documentation
 - × SAR, TBE, procedures, plant documentation (such as el. system analysis), is updated continuously with new knowledge
- Verifying integral tests
 - × Transition to house load (successfully several times)
 - × Division-independence test ("sid-oberoende test", tests to verify the integrity of the sub-divisions)
- Plant modifications
 - × "Larger" batteries (longer SBO coping time for steam driven pumps)
 - × New main generators (allows larger voltage excursions in the grid without affecting on-site power system)
 - × Adjusted Power System Stabilizers (damping of power oscillations)
- Fault-clearing system
 - × Increased selectivity between rectifiers and inverters
 - × New alarm for zero-sequence current in transformer neutral (detecting open-phase conditions)
 - × Improved fault-clearing system isolating safety bus if voltage or frequency goes outside defined operating area

3.3 OSKARSHAMN

Oskarshamn nuclear power station is situated on the East coast of Sweden, South of Stockholm, with three units, Oskarshamn 1, 2 and 3. All three units are BWRs. Unit 1 is connected to the 130 kV grid, whereas Units 2 and 3 are connected to the 400 kV transmission network. The secondary infeed of power is from the 130 kV network where also a gas turbine is available as backup. The 400 kV and 130 kV systems are interconnected via the system transformer T7. In figure 3.2 a simplified diagram of the off-site power system is shown.

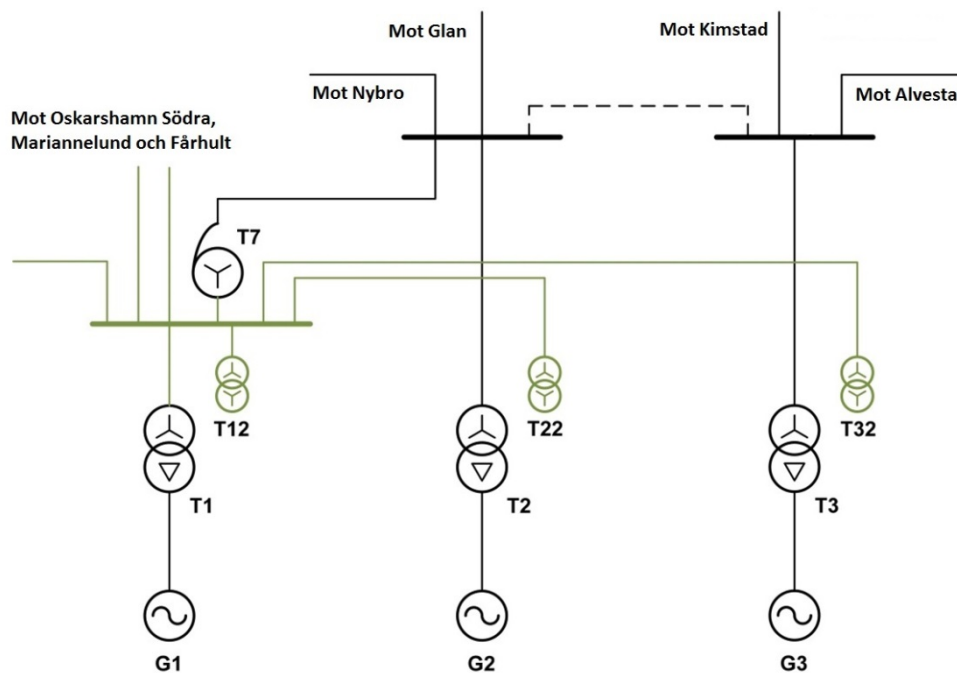


Figure 3.3. Simplified diagram of 130 kV (green) and 400 kV network connections of Oskarshamn.

Some notable events at Oskarshamn follow.

June 5, 1982

On 5 June 1982 a single phase-to-earth lightning fault hit the 400 kV line from Kimstad to Simpevarp near Simpevarp. Oskarshamn 1 and Oskarshamn 2 were both in service and operated at 350 MW and 425 MW respectively. The fault on the 400 kV line from Kimstad was correctly cleared but the circuit-breaker in Nybro for the 400 kV line from Simpevarp to Nybro was also tripped. The tripping of the circuit-breaker in Nybro disconnected Oskarshamn 1 and Oskarshamn 2 from the 400 kV network. The tripping was the result of an incorrect operation of the line protection system in Nybro.

It was believed that the fault currents on the 400 kV line from Kimstad to Simpevarp induced high-frequency disturbances between the line traps in Simpevarp and Nybro. In Nybro these disturbances were probably interpreted as an acceleration signal.

After the disconnection of the two 400 kV lines Oskarshamn 2 was connected to the 130 kV network via the 400/130 kV system transformer T7 and Oskarshamn 1 was connected directly to the 130 kV network. The forced outage of the two 400 kV lines initiated severe electromechanical oscillations with growing amplitude and Oskarshamn 1 and Oskarshamn 2 suffered dynamic instability. After some 11 s the first 130 kV line tripped due to out-of-step condition. A sequence of line disconnections then caused the disconnection of some 200 MW load in Småland.

August 4, 1992

A similar disturbance occurred on the 4 August 1992 when a single phase-to-earth lightning fault hit the 400 kV line from Kimstad to Simpevarp, near Simpevarp. The line protection system for the 400 kV line from Kimstad to Simpevarp operated

correctly. The line circuit-breaker in Simpevarp interrupted the current in the faulty phase, but not in all phases. The line protection system in Kimstad operated after some 120 ms and the line circuit-breaker there operated in all three phases after 160 ms. The distance relay in Simpevarp (RAZOG) for the 400 kV line from Simpevarp to Alvesta operated incorrectly for the fault in the reverse direction and tripped the line circuit-breaker in Simpevarp. Oskarshamn 3 was for a short while connected to the rest of the power system via one phase (perhaps two phases) of the 400 kV line from Kimstad to Simpevarp. Oskarshamn 3 supplied charging current to one phase (or two phases) of the 400 kV line to Kimstad when the line circuit-breaker in Kimstad had operated. The charging current was large enough to prevent the breaker failure protection relay to reset and Oskarshamn 3 was eventually disconnected from the rest of the power system.

The line circuit-breaker was tested and it was found that the operate time of one pole was too long and the operate mechanism was replaced by a new one.

The distance relay for the line from Simpevarp to Alvesta was also tested and it operated as designed. It was a self-polarized distance relay and it was energized from a capacitor voltage transformer (CVT). The accuracy of a CVT during the first period is not well defined it was believed that the output from the CVT changed sign when the fault occurred.

All distance protection relays of type RAZOG on the 130 kV and the 400 kV networks were replaced in 2005. The 400 kV circuit-breakers were replaced when the substation Ekhyddan was constructed and taken into service.

June 16, 2008

On 16 June 2008 the 130 kV line from Hultsfred to Simpevarp was hit by a lightning stroke that caused a high-resistance single phase-to-earth fault 11 km from Simpevarp. The 130 kV line has poles made of concrete and has suffered from at least one high-resistance earth fault on a previous occasion (1987-07-28). The fault was detected by the third step of the non-directional definite time residual overcurrent relay (JS3) and the line circuit-breaker was tripped. The unit circuit-breaker and the generator circuit-breaker for Oskarshamn 1 were tripped from a definite-time residual overcurrent relay. It is known that these definite-time residual overcurrent relays do not provide selective clearance of small zero-sequence currents.

After the fault clearance the de-energized 130 kV line was hit by another lightning stroke which caused a flashover in the open pole in the circuit-breaker and caused a fire in the switchyard. The initial power system fault was then followed by three more separate power system faults. The result was that the 130 kV bus-bar A and the 130 kV bus-bar B both were de-energized together with the startup transformer T32 for Oskarshamn 3.

July 13, 2010

On 13 July 2010 Oskarshamn 3 was disconnected from the rest of the power system at a power system fault on the 400 kV line from Simpevarp to Alvesta caused by a lightning stroke. The line protection system operated correctly and the line circuit-breakers operated correctly and cleared the fault. The under-impedance protection relay in Oskarshamn 3 picked up correctly but it did not reset properly. After 0.8 s the protection relay tripped and disconnected Oskarshamn 3 from the rest of the power system.

The faulty relay was replaced by a new one.

September 10, 2013

On 10 September 2013 the step-up transformer T3 in Oskarshamn 3 was energized from Ekhyddan. At the time of the energization the switchyard Ekhyddan FT62 was electrically connected to the switchyard Ekhyddan FT61. All four outgoing 400 kV transmission lines and the 400/130 kV system transformer T7 were connected to the two interconnected switchyards FT61 and FT62. The generators for the plant G1, G2, and G3 were all out of service. After the energization of T3, the unit circuit-breaker for the step-up transformer T1 in Oskarshamn 1 was tripped unexpectedly and unwantedly from the low-set independent-time residual overcurrent protection (JS3).

Other registrations and investigations indicate that the equipment for controlled switching of circuit-breakers is not configured and tuned optimally.

The earth-fault protection in the distance protection for T1 in Oskarshamn 1 did not operate as expected. Tests show that the second harmonic restraint does not prevent tripping if the residual current in the bay is lower than 540 to 636 A. The recorded RMS value of the residual current is 392 A and the computed fundamental frequency component is 218 A. According to the manual for the relay protection the second harmonic restraint should block the tripping if the second harmonic current is higher than 49 A. The computed second harmonic current is 257 A. The wording in the manual does not describe the second harmonic restraint correctly.

July 13, 2014

On 13 July 2014 Oskarshamn 3 was disconnected from the rest of the power system caused by a single phase-to-earth fault on the 400 kV line from Ekhyddan to Alvesta and an incorrect operation of the line protection system in Kimstad for the 400 kV line from Kimstad to Ekhyddan. The directional independent-time residual overcurrent relay (JS1) operated unwantedly. The phase-to-earth fault occurred close to voltage zero, which caused a high DC component. A high DC component in the residual current has caused some overreach of the current relay JR1 but this is not the only explanation to the incorrect operation. The setting of JR1 may have been incorrect, the calibration may have been incorrect or the independent-time relays for JR2 or JR23 might have operated instantaneously.

Oskarshamn 3 successfully entered island operation and successfully tripped to house-load operation after about 25 s. Transfer to house-load operation was initiated by over-frequency protection that was installed during modernization of the 400 kV substation Ekhyddan.

3.3.1 Mitigating actions taken at Oskarshamn

Below are some actions that in studies have been recommended for the grid connection of Oskarshamn NPP and in the nearby grid, of which most have been implemented:

- By modernizing the line protection the SUB2 fault-clearing times can be decreased for remote shunt faults on outgoing 130 kV lines towards Oskarshamn Södra I and II, Hultsfred and Fårhult, in case of non-operating SUB1 distance protection.
- Assess the possibility to duplicate the bus-bar protection for the 130 kV substation, since the existing is old and delivery time for spare parts is long. Operating the

substation without bus-bar protection would not harmonize with today's high standards of security.

- Install 130 kV and 400 kV breaker-failure protections for system transformer T7, between 400 kV and 130 kV systems, to increase the security in the protection system.
- Duplicate the bus-bar protections in 400 kV substations Simpevarp, Glan, Kimstad, Alvesta and Nybro. Non-functioning bus-bar protection in double-breaker substations has serious consequences, since it is often understood that a shunt fault in a double-breaker substation will not lead to any degradation in the network. A non-functioning bus-bar protection will then lead to loss of all connected lines with a fault time of about 500 ms. Kimstad substation has not yet been upgraded.
- Add extra communication channel for SUB2 protections in order to decrease fault-clearing times for shunt faults close to Glan, Kimstad, Alvesta and Nybro on 400 kV lines from Simpevarp.
- Assess the possibility to change the configuration of the 130 kV substation Simpevarp so that the two incoming lines to Oskarshamn 1 are separated.
- Tuning are done of the controlled switching of circuit-breakers in Ekyddan.

The following are mitigating actions taken at the NPP:

- Main generators and large transformers
 - × Verification by tests, transition to house-load operation
 - × Adjust function and setting of the out-of-step protection to assure isolation of the unit for shunt faults leading to out-of-step conditions. Disconnection should be initiated prior to full phase opposition. The protection has been replaced on Oskarshamn 3.
 - × Adjust the under-voltage protection in order to isolate the unit from the grid and enable transfer to house-load operation while still possible
 - × Modified settings of under-frequency protection
 - × Reduced delay and reach of the under-impedance protection for Oskarshamn 1 and Oskarshamn 2. The under-impedance protection is backup protection for shunt faults on 130 kV and 400 kV bus-bars respectively in Simpevarp, but is not to function for faults further out in the network
 - × Over-voltage protection changed for disconnection of generator circuit-breaker before unit circuit-breaker
 - × Exchanged all old large transformers
 - × Installation of new earthed shield between primary and secondary sides in new transformers
 - × Installation of new surge arresters on the secondary side in new transformers (6.3 and 10 kV side)
- Bus-bars
 - × Installation of new under-voltage protection on safety bus-bars
 - × Installation of new under-frequency protection on safety bus-bars (Oskarshamn 2)
 - × Moved functions for the diesel units' long-term operation from UPS bus-bars to diesel bus-bars, i.e. diesel cooling
- Power electronics
 - × Increased selectivity between rectifier and inverter in UPS units
 - × Analyses and/or tests on rectifiers and UPS units with voltage transient
 - × Installation of an automatic external by-pass for UPS units (Oskarshamn 2)
 - × New over-voltage protection installed in new rectifiers, manual restart necessary

- × Duplicated battery backed power sources to critical equipment, I&C-cubicles, RPS
- RAMA, severe accident filter
 - × New local diesel generators for RAMA, severe accident filter
- Documentation
 - × A new method for analysis of external disturbance events and events from the main generator. The method secure a correct analysis of events
 - × Document for new demands on voltage and frequency, for UPS units and rectifiers
 - × New instructions for manual restart of rectifiers and UPS units
 - × Compensatory actions to cope with loss-of-phase events

3.4 OLKILUOTO

The Olkiluoto Nuclear Power Plant is on Olkiluoto Island, which is on the shore of the Gulf of Bothnia in western Finland. The Olkiluoto plant consists of two Boiling Water Reactors (BWRs), Olkiluoto 1 and 2.

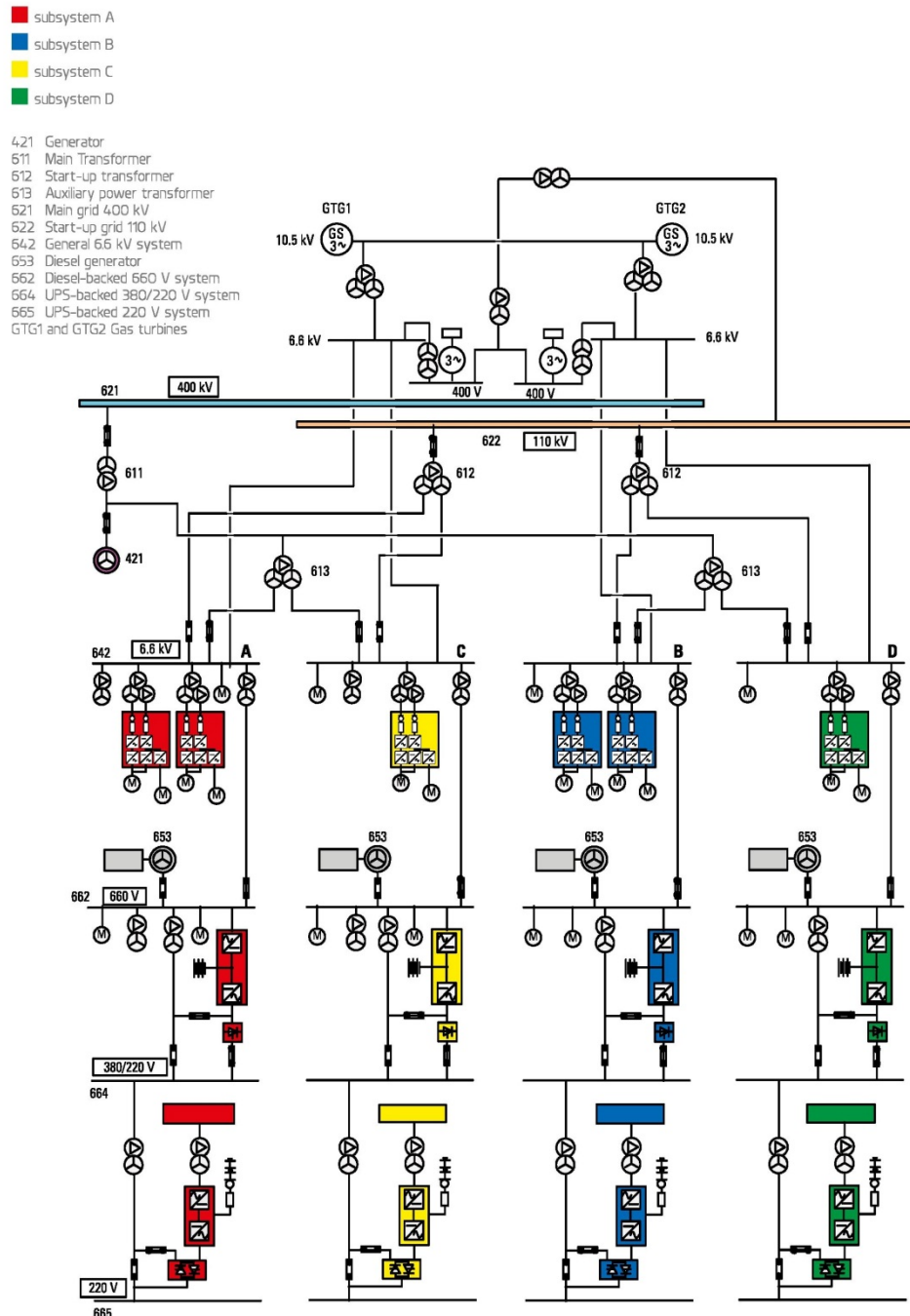


Figure 3.4. Simplified diagram of Olkiluoto 1 and 2 connection to grid. From www.tvo.fi.

May 30, 2008

On May 30, 2008, the yearly maintenance outage at Olkiluoto 1 (OL1) was over and power of the unit was being raised. At 60% power level, the generator excitation system caused high excitation current, and the generator output voltage rose to 125% of the nominal 20 kV. The over-voltage relay (115% / 6 s), intended to drop the plant to house load operation in grid over-voltage situations, opened the circuit-breaker on the high-voltage side of the main transformer, disconnecting the plant from the 400 kV grid. When connection to the 400 kV grid was lost the voltage at the plant's 6.6 kV bus-bars rapidly peaked to around 150% for a duration of 150 ms. The main and house load transformers saturated, and their differential protection opened the generator switch and initiated a turbine trip. Electric pumps supplying hydraulic steering oil to the steam dumping valves stopped, preventing dumping of steam to the turbine condenser and leading to an automatic reactor trip and closing of the main steam isolation valves on both sides of the containment wall. The switch-over automatically connected the plant to the alternative 110 kV grid after a 2 s blackout time.

3.4.1 Mitigating actions taken at Olkiluoto

During the recent years the following issues have been studied (issues which are linked to grid connections):

- Over-voltage (power-frequency overvoltage)
Grid connections and the main generator together with grid. Not lightning and other fast or very fast transients, where original studies are still valid. (The protection against lightning and other fast or very fast transients is based on the original design, with some small changes.)
- Under-voltage
For example slowly decreasing voltage at grid side
- Phase unbalance at grid side (year 2008)
- Grid connections (400 kV and 110 kV) with only one phase or two phases connected
- GIC (Geomagnetic Induced Currents) studies have been made during the main transformer replacement project
- SSR (Sub-Synchronous Resonance) monitoring equipment has been installed and used during the FennoSkan 2 DC-link commissioning phase (OL2 only). The equipment is not in operation at the moment

The following lists the actions taken at the plant:

- Modifications to the 380 VAC UPS (system 664). New over-voltage limiter and selectivity improvements
- Diesel secured bus-bar (system 662) voltage measurements are recorded in measurement computer. More frequent voltage information which is needed in disturbance investigations
- The co-operation between TVO and Fingrid (grid operator) has been improved. If plant unit is only connected to either 400 kV or 110 kV network, no functional tests are allowed which might jeopardize this connection. Such tests are done to the grid which is not connected
- Phase disturbances in the grid connections were analyzed with help of simulations. Potential for improvement for safety bus-bar (system 662) under-voltage protection in the range of 65-85% and under-frequency protection. This is still under investigation

- In the new system 313 main circulation pumps extra inertia are applied into the rotating parts. Separate fly-wheel motors and frequency converters are no longer needed
- Movable aggregates have been renewed and the number has been increased

Under- and over-voltages in unit network during different operational and disturbance situations have been evaluated with simulations. Disturbances from the national grid, Olkiluoto switchyards, transformers and main generator were considered. The function of the generator was also simulated in situations where the automatic voltage regulator fails and increases the voltage to maximum.

Based on these studies the following protection changes were implemented:

- Over-voltage protection to plant unit transformer circuit-breakers (system 613) was added (6.6 kV, system 642)
- Over- and under-voltage protection of main circulation pump and frequency converter breakers (system 649) was added (6.6 kV, system 642)
- Generator block over- and under-voltage protection tripping matrix was changed
- Tripping times of bus-bar protection and breaker failure protection in the 400 kV switchyard were increased
- Interlocking between the generator circuit-breaker and the unit circuit-breaker was implemented
- Protection of simultaneous high voltage and high excitation current was added
- Operators were instructed in certain operational and disturbance situations to lower the power to a level where the 649 system fly-wheel generators are not necessary for ensuring the fuel integrity

4 Toolbox of Possible Mitigating Actions

Particularly since the incident in Forsmark on July 25, 2006 extensive studies have been performed on the Nordic NPPs' vulnerabilities towards events in the off-site power system. One tool utilized has been to assess possible events in the network (represented as voltage profiles) and, by, simulations/calculations estimate the response from equipment and protection systems in the grid and in the NPP.

However, these actions have not prevented events at the NPPs that have caused concern with the authorities (SSM). By gathering experiences from NPPs around the world and within four of the Nordic NPPs have in this study led to four "tools" or mitigating actions, presented below.

The first tool is detection of loss-of-phase, which is presented since this phenomenon was brought to attention by the event in Forsmark on May 30, 2013.

The second tool addresses the issue of keeping the nuclear units connected to the grid in case of close-up faults in the network in combination with a non-functioning fault-clearing system (circuit-breaker). By reducing the fault-clearing time the ability for the NPP to stay synchronized to the grid is increased. The tool presented is double circuit-breakers in series.

The third and fourth tools do not address specific technical problems but are higher level concepts, or methods to address the problems, to prevent future incidents and possible events of station blackout. The tools are the concept of "withstand or isolate" and duplicated analyses.

4.1 DETECTION OF LOSS-OF-PHASE

This tool aims at a specific technical problem, which has been somewhat overlooked up to the events in Byron 2 on January 30, 2012 and Forsmark 3 on May 30, 2013. As described above, a non-functioning breaker resulted in a situation where Forsmark on-site power experienced an unsymmetrical voltage; two phases on the incoming 400 kV supply were lost. The faulty condition was not detected by any protection system until motors were thermally overloaded.

The experience at Forsmark resulted in investigations at Nordic nuclear power plants to determine the vulnerability to this type of events.

Below is a description of a possible way to detect loss-of-phase for the off-site power supply using existing Intelligent Electronic Devices (IEDs) with its inputs from current transformers located on the high-voltage side of the step-up transformer and start-up transformer. The described method has a Swedish patent pending (SE 1400207-5). It can be noted that there are other ways to detect loss-of-phase, as three-phase voltage protection or negative-sequence voltage protection. This method has the advantages that

- it can be implemented in existing IEDs,
- classifies the type of unbalance, one phase or two phases, together with information on which phases are lost,
- the type of application or process that is monitored has minimal impact on the settings of the protection,
- it is sensitive enough to protect, for example, asynchronous machines.

The protection is not to function for three-phase interruptions, i.e. only phase unbalance with loss of one or two phases will lead to function. An important criterion is also that current in at least one of the phases is above a certain threshold value, S .

Six test values, based on the magnitude of the phase currents, are defined; for loss of one phase D_a , D_b and D_c , and for loss of two phases D_{ab} , D_{bc} and D_{ca} . Small values implicate loss of that one or two phases, large values does not. Test values D_a , D_b and D_c are defined as

$$D_a = \frac{2|i_a| + \varepsilon}{|i_b| + |i_c| + \varepsilon}, \quad D_b = \frac{2|i_b| + \varepsilon}{|i_c| + |i_a| + \varepsilon}, \quad D_c = \frac{2|i_c| + \varepsilon}{|i_a| + |i_b| + \varepsilon}$$

Test values D_{ab} , D_{bc} and D_{ca} are defined as

$$D_{ab} = \frac{|i_a| + |i_b| + \varepsilon}{2|i_c| + \varepsilon}, \quad D_{bc} = \frac{|i_b| + |i_c| + \varepsilon}{2|i_a| + \varepsilon}, \quad D_{ca} = \frac{|i_c| + |i_a| + \varepsilon}{2|i_b| + \varepsilon}$$

In the equations above ε is a small value that prevents division by zero.

The test values are compared to threshold values (T_0 and T_1) to detect loss-of-phase. The threshold values shall fulfill the conditions, $0 < T_0 < 1$ and $1 < T_1 < M$, where M is a large number.

In table 4.1 the different criteria for detection of loss of one or two phases are shown. For function it is required that S , C_1 , C_2 and C_3 are all fulfilled.

Table 4.1. Table defining the different criteria for detection of loss of one or two phases.

State	Criteria		
	C_1	C_2	C_3
Loss of phase a	$D_a < T_0$	$D_b > T_1$	$D_c > T_1$
Loss of phase b	$D_a > T_1$	$D_b < T_0$	$D_c > T_1$
Loss of phase c	$D_a > T_1$	$D_b > T_1$	$D_c < T_0$
Loss of phase a and b	$D_{ab} < T_0$	$D_{bc} > T_1$	$D_{ca} > T_1$
Loss of phase b and c	$D_{ab} > T_1$	$D_{bc} < T_0$	$D_{ca} > T_1$
Loss of phase c and a	$D_{ab} > T_1$	$D_{bc} > T_1$	$D_{ca} < T_0$

4.2 DOUBLE BREAKERS, IN SERIES

The only relevant reason for long fault-clearing times, in a protection system with duplicated protections, is a non-functioning breaker. In a double-breaker arrangement a non-functioning breaker results in a delayed fault-clearing time, but normally only disconnection of one of two bus bars and no disconnection of healthy lines or transformers. Both NERC [3] and IEEE [4] note the possibility to use two breakers in series; both receiving trip signals from the relay protection system. This arrangement will decrease the fault-clearing time in case of a non-functioning breaker. [5]

To quote the IEEE standard:

“In those cases where stability studies show that the critical clearing time is less than the shortest backup clearing time attainable with high-speed breaker failure protection schemes, the only solution may be to install two identical breakers in series, with both

breakers being tripped simultaneously by the protection schemes. With this arrangement, and fully redundant protection schemes, instrument transformers, and control power sources, it can be assumed that at least one of the breakers will successfully interrupt the fault. Thus, the total clearing time will be the same as the primary clearing time, and no breaker failure scheme is necessary.” [4]

The concept has not been widely used, and to the knowledge of the author only been implemented at a few locations.

A typical double-breaker arrangement is shown as a) in figure 4.1. The concept results in a high reliability and the consequences of a bus-bar fault will not result in any loss of any bays (lines or generator in the figure). The double-breaker arrangement is highly utilized in many transmission and sub-transmission networks, e.g. by Svenska kraftnät. The reliability is ensured by duplicating the components of the fault-clearing system, i.e. protection functions, relay protection, current-transformer cores, trip coils, etc. However, it has not been practice by many network owners to duplicate the circuit-breakers. This implies that a bus-bar fault or line fault in combination with a non-functioning circuit breaker will result in fault-clearing times governed by the breaker-failure protection, i.e. ~170 ms.

By duplicating also the circuit-breaker in the double-breaker arrangement this delay of fault-clearing time, due to breaker-failure protection, can be eliminated. The corresponding arrangement is shown as b) in figure 4.1.

The alternative c) in figure 4.1 is an arrangement that inherits some of the benefits from b). By adding a line circuit-breaker on the outgoing lines the delayed fault-clearing time for close-up line faults on these lines is eliminated, in case of a non-functioning circuit-breaker. However, the benefits from the series circuit-breaker arrangement are lost for bus-bar faults. This arrangement could be an attractive way to build new lines in order to fulfil the demands for fault ride-through capability.

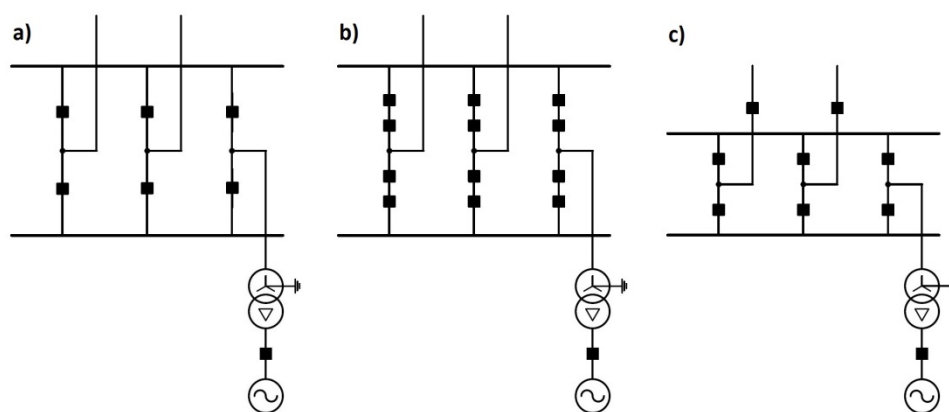


Figure 4.1. Different double-breaker arrangements. Figures from [5].

4.2.1 Comparison for different failure modes

It is important to compare the arrangements for different failure modes to see pros and cons for the different arrangements regarding reliability.

Failure modes can be divided into at least three groups: active failure events, passive failure events and stuck-condition of breakers.

Active failure events

Short-circuit faults are the most common faults in power systems and can occur in all types of components in the primary system. Short circuits will cause appropriate circuit-breakers to trip to disconnect the fault. This type of event is defined as an active failure event.

By comparing the standard double-breaker arrangement to the double-breaker arrangement with two circuit-breakers in series, the impact on the power system for an active failure event will be the same.

Passive failure events

Passive failure events are failure events here considered as inadvertent operations of circuit-breakers, due to faults within the protection system or associated equipment or due to a failure in the circuit-breaker itself. It can also be due to manual operating errors.

By studying the double-breaker arrangements a) and b) in figure 4.1 it can be seen that due to the two paths from a line or transformer to the two bus-bars, both arrangements are quite insensitive to inadvertent operations of a single circuit-breaker. For the arrangement c) in the figure the added line circuit-breaker introduces a possible source of concern. However, not adding an additional series breaker to the transformer bay minimizes the risk for unwanted disconnection of the unit.

Stuck-condition of breakers

Because of their switching function circuit-breakers can exhibit a third failure mode; failing to operate or a stuck circuit-breaker condition. When a short-circuit occurs and a circuit-breaker, or one or more poles in the circuit-breaker, fails to trip due to faults within the protection system or the circuit-breaker itself, backup or secondary protection must operate, with a prolonged fault-clearing time and likely to outage a greater section of the system.

By studying the arrangements in figure 4.1 the advantage of the duplicate circuit-breaker in series is obvious. A non-operating circuit-breaker (or one or more of the poles) in a series arrangement will not lead to a prolonged fault-clearing time since the adjacent circuit-breaker will operate. The arrangement c) in figure 4.1 also minimizes the fault-clearing times for close-up line faults, where two circuit-breakers operates in series. However, not so for bus-bar faults; where only the currents from the outgoing lines are cleared by circuit-breakers in series (not the currents from the adjacent bus-bar or the generator).<

There is also a possibility for a breaker pole not to close when energizing the closing coil. With two circuit-breakers in series the possibility for this kind of fault increases.

4.2.2 Possibilities to retrofit

The substations in the 400 kV network at Forsmark and Oskarshamn has recently been rebuilt and the units are now connected to modern double-breaker substations and it is probably not possible to replace the single circuit-breakers with two circuit-breakers in series, due to the limited space. The 400 kV substation at Ringhals has not been rebuilt since commissioning and in case of future modernization the concept of series circuit-

breakers should be evaluated. At Olkiluoto it does not seem possible to add breakers in series.

There might be a possibility to retrofit existing double-breaker substations with a third line circuit-breaker, according to arrangement c) in figure 4.1. With this arrangement the line circuit-breaker will not be located between the bus-bars but along the incoming line close to the switchyard.

Table 4.2. Pros and cons with the different configurations in figure 4.1.

Configuration	a)	b)	c)
Pros	Well proven design Compact Low number of components	No prolonged fault-clearing times Minimizing the part of the system suffering from outage	No prolonged fault-clearing times for close-up line faults Easier than b) to retrofit in existing station
Cons	Non-functioning breaker leads to prolonged fault-clearing times Non-functioning breaker can lead to outage in larger part of the system	Requires larger footprint in the station Higher number of components Difficult to retrofit in existing station	Same cons as a) for bus-bar faults

4.3 DUPLICATED ANALYSES AND AVOIDING COMMON-CAUSE ERRORS

The previous section considered the possibility to duplicate circuit-breakers in order to increase reliability. As mentioned the reliability is generally ensured by duplicating the components of the fault-clearing system, i.e. protection functions, relay protection, current-transformer cores, trip coils, etc.

Within the nuclear power a considerable effort is put into quality assurance of reports and other documents, often with procedures involving several levels of review, in order to assure the reliability of the contents.

From practical and economic reasons technical analyses of protection relay settings etc. are often performed

- By the same person that has performed previous analyses
- By different person, but using data from previously performed analyses
- By only one person (even if several persons review the work)
- Results/settings from analyses are often “inherited” by other units in the same station or even by other nuclear power stations

This may result in a kind of common-cause situation; a result or setting is accepted as valid by several users/units with a limited review. In the Swedish nuclear power industry many analyses were performed in the 70’s or early 80’s. The performing engineers are in many cases no longer available and limited documentation and background to analyses can result in accepting strategies/settings/results on vague grounds.

Within medicine it is a well-known concept to get a second opinion from another physician in order to get more information or to hear a differing point of view. By doing so, a more well-informed decision can be made, with higher reliability.

A possible way to improve the reliability of analyses, relay protection schemes and settings could be to, for example

- Let two engineers perform the same analysis independently
It could be that technical analyses (e.g. calculation of physical or electrical properties or relay protection settings) are performed by the contractor as part of a purchase agreement. This could open for the possibility of the NPP's engineers to independently perform the same analyses.
- Do not use existing reports or analysis as basis for the renewed analysis
By reading a previous analysis report the engineer most certainly will be biased.
- Diversify by using different entrepreneurs
When purchasing and installing apparatuses and systems a way to avoid common-cause errors is to use different brands, manufacturers and/or models of the equipment, e.g. for SUB1 and SUB2 relay protection. The idea is that a latent fault in one model does most probably not exist in a model of another brand or manufacturer. The same thinking can be used in the analysis phase.

It may be difficult to implement this strategy to a full extent, due to economic and practical reasons. However, for the most critical parts and functions of the system it is not un-realistic to increase the reliability by implement duplicate analyses. The costs for analyses are on the same magnitude as relay protection devices.

4.4 CONCEPT OF "WITHSTAND OR ISOLATE"

All electric equipment is intended for a specific electromagnetic environment and specific conditions, within which it is to operate and behave in a predictable manner. The environment may be defined by e.g. voltage levels, voltage unbalance (between supplying phases), frequency of the supply voltage, etc. If for example the supply voltage to an apparatus increases beyond the specified levels the behavior of the apparatus may at first not be predictable. If the voltage level is even further increased, the apparatus may even be damaged, temporarily or permanently.

The most important aspect to the concept of "withstand or isolate" is to know where the boundary, i.e. the immunity of the critical equipment. The equipment must be able to operate as intended in the "withstand" area.

The protection system must be designed and operated to transfer the system from the "withstand" to the "isolate" states.

When in the "isolated" state there must be no possibility for transients or disturbances in the off-site power supply to transfer into the isolated on-site power system. This must hold for galvanic as well as for inductive and capacitive phenomena.

Applying the concept to the supply voltage of an apparatus this can be illustrated by for example the ITIC curve in figure 4.2. The figure shows two areas of conditions for which the equipment must be isolated; "over-voltage conditions" and "under-voltage conditions", and one area representing the operating conditions the equipment can withstand; "acceptable conditions". It is worth noting that the acceptable supply voltage may vary in level depending on the duration of condition. In steady state the

ITIC curve is represented by a relatively narrow interval around 100% voltage level. For more transient behaviors, e.g. 100 μ s, the acceptable variation in voltage level is considerably larger.

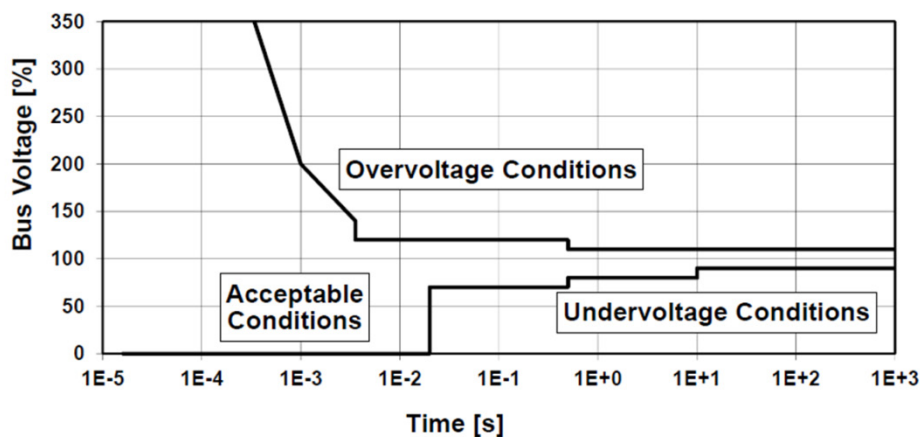


Figure 4.2. The ITIC curve. [7]

The concept of “withstand or isolate” is highly connected to electromagnetic compatibility, or EMC, where the goal is the correct operation of different equipment in a common electromagnetic environment. There are standards developed on the subject of EMC in general and also on EMC immunity. Between the licensees Vattenfall and OKG Technical Requirements (TBE and KBE) for electrical equipment within Swedish nuclear power generation are available at www.tbekbe.se. These requirements are applicable to vendors of equipment to the nuclear power plants. TBE101 is on the topic of “Environmental Specification for Normal Operation” and immunity requirements are given, which are according to IEC 61000-6-2.

4.4.1 How to obtain the immunity level

The immunity for equipment must be obtained to a certain level of accuracy, depending on how critical the function of the equipment is.

From experiences within the NPP facilities it can be concluded that equipment like rectifiers and inverters, i.e. non-passive components, have not always operated as intended.

The method of obtaining the immunity levels may vary and may include;

- Relying on manufacturer data
For less critical equipment this may be sufficient. The equipment can be manufactured according to specific standards on EMC.
- Performing theoretical analyses or simulations
As a complement to available manufacture data it may be necessary to perform analyses of how the equipment will behave under certain conditions, such as low short-circuit power, unbalanced conditions, during transients, etc. To obtain information of how different components behave together this may also be necessary.
- Estimating the immunity from registrations of earlier events
Information of the immunity can be concluded from registered events where the

equipment both have succeeded and failed to operate as intended. Having a sufficient amount of such registrations can serve as a basis for such estimation. See example in section 4.4.4.

- Performing tests on equipment
Sometimes the only (but always the best!) way to get information on the immunity of a component or equipment is to perform testing to see under what conditions it will operate as intended. The types of tests correspond to the previous bullet, where registration of events is used instead of deliberate tests. This could be low voltage conditions, unbalanced voltage conditions, low short-circuit power conditions, etc., depending on the equipment.

4.4.2 The importance of the protection system

To successfully implement the “withstand or isolate” concept it is important that the protection system is able to detect and act when the conditions are outside what the equipment withstands. This means that sensors giving input to the protection system, e.g. current transformers and voltage transformers, are able to operate and detect fast transients, etc. The bandwidth of the protection system must be coordinated with the sensitivity of the protected equipment. This also hold for conditions such as voltage unbalance; if the equipment is sensitive to unbalanced conditions the protection system must be designed to detect such conditions.

The protective functions must also be sufficient to cover the relevant network conditions and physical quantities, i.e. current, voltage and frequency.

When the protective system operates, and designated circuit-breakers are tripped to isolate the on-site power system, the isolation must be fast enough to not jeopardize the function of the equipment.

4.4.3 Uphold sufficient level of isolation

Given that the critical equipment is isolated from the degraded power system it is important that the level of isolation is sufficient. Circuit-breakers that have tripped form a galvanic barrier between the two systems and it can be anticipated that the insulation is sufficient to prevent flashovers. However, it is important to keep the system isolated also with respect to inductive and capacitive phenomena, e.g. not use the same cable channels for cables (signal or power) belonging to the off-site and on-site power systems.

4.4.4 Example from the Industry

Even though the nuclear power plants represent a somewhat unique part of the power system with high demands on power supply regarding reliability and redundancy, other electric power producers and consumers may be equally or more sensitive to disturbances in the power supply.

One example is presented here to illustrate the concept of “withstand or isolate” by investigating the immunity of the apparatuses and processes to disturbances and take actions to either minimize the disturbances, to increase the immunity or better define the limit for when to isolate.

In 2003 a joint project with network utilities and pulp and paper industries was completed and several studies were performed on how costs relating to power quality disturbances can be minimized. [2]

One type of disturbance has specific interest to the pulp and paper industry; voltage dips, i.e. when the voltage in one or more phases drops significantly during tens of milliseconds up to some hundred milliseconds. The voltage dip is often the result of a short circuit in the power system.

For one pulp and paper industry in particular these voltage dips resulted in several production stops each year, resulting in loss of income. By recording (using power-quality equipment) the voltage dips and investigating which of the dips that resulted in production stops an immunity curve could be obtained.

In figure 4.3 the voltage dips are plotted in a voltage/duration graph. It can be seen that most of the dips have durations between 50 and 110 ms. The voltage level of the dips varies between 10 and 95% with the majority of the dips above 50%. As can be seen from the figure, deeper voltage dips result in more production stops.

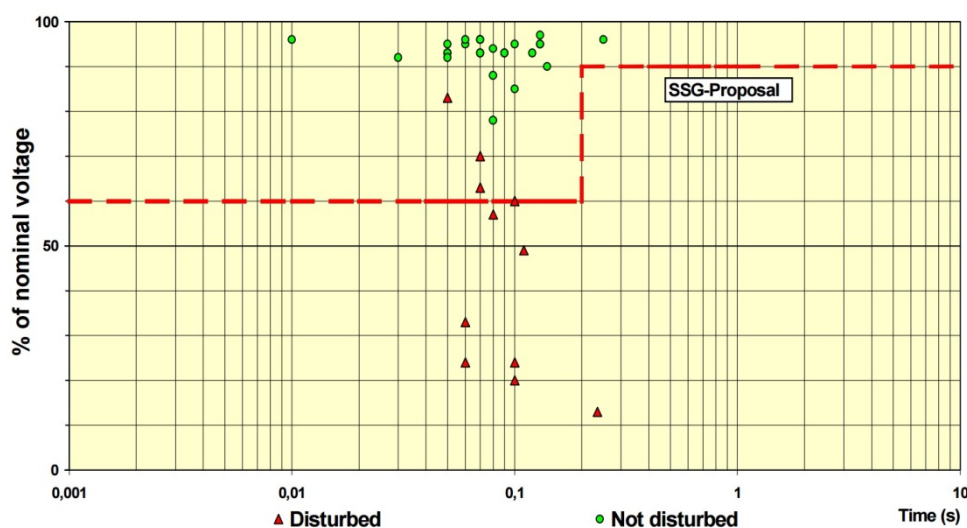


Figure 4.3. Recorded events (voltage dips) and the ability of the process to withstand the dip or not. [2]

Investigations like this, corresponding to bullet 3 in section 4.4.1, give valuable insight on the immunity of the equipment, but also the quantification of how the industry would benefit from a higher immunity.

The idea of the line “SSG-Proposal” is to indicate that there is, or should be, a divided responsibility between the service provider (TSO or DSO) and the customer/industry. In short; it is the service provider’s responsibility to minimize the number of voltage dips below the curve and it is the customer’s responsibility to tolerate the voltage dips above the curve. The exact positioning of this “line”, or divided responsibility, is subject to discussion between the parties. The case above is a typical example of applying the withstand-or-isolate concept.

5 Conclusion and Future Work

This report has presented a short survey in available literature on events at NPPs around the world that has been triggered from the off-site power system. Even if a lot of events are found in databases, not many have been relevant for the scope of this report. However, four events are presented in some more detail and the main “lessons learned” from these events could be summarized as:

- The reliability of critical on-site equipment must be ensured
- Training of personnel to handle situations of loss of off-site power is important
- Perform testing to ensure proper function of equipment and procedures
- Assess (by simulations and experienced events) the immunity of the plant towards events in the off-site power system

A number of events related to loss of off-site power and mitigating actions at four Nordic NPPs are presented in the report. Amongst the actions performed, in particular since the incident in Forsmark on June 25, 2006, can be noted:

- Improvement of the fault-clearing system in the off-site power system to minimize fault-clearing times and improve reliability
- Improvement of the relay protection system for main generators, transformers, etc.
- Extensive studies of the units’ ability to withstand disturbances in the off-site power system
- Improved communication between the NPP and the network operator, together with carefully planned and executed revised outages and maintenance work in the power system, to ensure a reliable operation of the plant
- Verification of transfer to house-load operation by test
- Special attention given to selectivity of protection for rectifiers/inverters for battery-secured systems
- Ensure that new components in the electric system do not lead to a more vulnerable or sensitive system, or invalidate results from previous analyses of the reliability of the system

Four possible “tools” are presented in the report that could be further investigated and applied to minimize future incidents and events related to loss of off-site power.

The first tool is a method to detect loss-of-phase, which is presented since this phenomenon was brought to attention by the events in Byron 2 on January 30, 2012 and Forsmark 3 on May 30, 2013. The method presented utilizes existing IEDs for step-up and start-up transformers.

The second tool addresses the issue of keeping the nuclear units connected to the grid in case of close-up faults in the network in combination with a non-functioning fault-clearing system (circuit-breaker). By reducing the fault-clearing time the ability for the NPP to stay synchronized to the grid is increased. The tool presented is double circuit-breakers in series.

The third and fourth tools do not address specific technical problems but are higher level concepts to prevent future incidents and possible events of station blackout. The tools are the concept of “withstand or isolate” and duplicated analyses.

It can be statistically concluded from the screening of databases a falling trend in the number of events per year in many countries, which is pointed out by the

Clearinghouse study. However, several recorded incidents show that unforeseen sequences of events may occur and it is difficult to suggest that no incidents will occur in the future that are not foreseen. This report has suggested a handful of tool that may be utilized in order to minimize the risk of this.

5.1 FUTURE WORK

The report suggests the following future work:

- The possibilities and practicalities in applying the “withstand or isolate” strategy to the NPPs. What equipment should be addressed? What are the best methods to obtain the immunity of the equipment? When isolated from the off-site power system, how is the level of isolation verified?
- Investigate further possible routines to increase the quality of studies and analyses by
 - × duplicating the analyses with different engineers, different contractors
 - × prevent common-cause errors by not re-using previous analyses results
 - × not assign the same engineer to repeatedly investigate a certain unit.

6 References

- [1] Lidström, E., Wall, D. and Persson, J., *Grid interference on operations, Mapping of R&D needs*, Elforsk report 2015-132.
- [2] Häger, M., Ceder, Å. and Thunberg, E., *A joint Power Quality project between Swedish network utilities and industrial customers*, Cigré C4-103, Session 2004.
- [3] *Protection System Reliability - Redundancy of Protection System Elements*, A Technical Paper, NERC System Protection and Control Subcommittee, North American Electric Reliability Corporation, Princeton, January 2009.
- [4] *IEEE Guide for Breaker Failure Protection of Power Circuit Breakers*, IEEE Standard C37.119-2005, Institute of Electrical and Electronics Engineers, New York, 6 March 2006.
- [5] Hermansson, H., Larsson, S., Lindahl, S. and Walve, K., *Kraftsystemets driftsäkerhet. Nuvarande och framtida dimensioneringskriterier*, 19 February 2015.
- [6] NUREG/IA-0430, *TRACE Simulation of SBO Accident and Mitigation Strategy in Maanshan PWR*, U.S. NRC 2013.
- [7] Arrilaga, J., Bollen, M.J. and Watson, N.R., *Power Quality Following Deregulation*, Proceedings of the IEEE, vol. 88, no. 2, pp. 246-261, February 2000.
- [8] *Operating Experience Assessment - Effects of Grid Events on Nuclear Power Plant Performance*, NUREG-1784, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC 20555-0001, December 2003.
- [9] *Susceptibility of Nuclear Stations to External Faults*, NUREG/CR-7175, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, September 2014.
- [10] Raughley, W.S., Lanik, G.F., *Operating Experience Assessment Energetic Faults in 4.16 kV to 13.8 kV Switchgear and Bus Ducts That Caused Fires in Nuclear Power Plants 1986–2001*, February 2002.
- [11] IAEA Specific Safety Guide No. SSG-34, *Design of Electrical Power Systems for Nuclear Power Plants*.
- [12] Available online at:
<https://nucleus.iaea.org/sites/nuclearpowerengineering/gridinterface/Shared%20Documents/LOOP%20and%20SBO%20Topical%20Study.pdf>

OPERATIONAL EVENTS IN OFF-SITE POWER SYSTEM

In this report some events from international and four Nordic NPPs are presented in which disturbances in the off-site power system have had impact on the on-site power system, and to some extent jeopardized the security of the plant.

Four “tools” are presented that could be further investigated and implemented in order to further increase the ability of NPPs to withstand disturbances in the off-site power system.

Another step forward in Swedish energy research

Energiforsk – Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter!

We are actively meeting current energy challenges by developing new ways to store energy, helping to create a fossil free transportation system, establishing new market models for the heat and power sector, developing new materials and regulating the grid. www.energiforsk.se