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Joint IAEA–NEA Workshop on the Current Implementation Status of Measures to Manage Open Phase Conditions in Electrical Power Systems of Nuclear Power Plants: Summary Report

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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27–29 October 2020
Online event

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

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Committee on the Safety of Nuclear Installations (CSNI)

The Committee on the Safety of Nuclear Installations (CSNI) addresses Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Foreword

Prior to the creation of the Nuclear Energy Agency (NEA) Working Group on the Safety of Electrical Systems (WGELEC), its members had already analysed the significance of open phase conditions (OPCs) for the safety of nuclear power plants in earlier activities. Based on this work, the International Atomic Energy Agency (IAEA) Safety Report Series No. 91 (IAEA, 2016a) was developed to better understand the impact of OPCs. Five years later, in 2020, a workshop was jointly convened between the NEA and IAEA to share experiences on the newly implemented detection and mitigation systems.

This report gives a comprehensive overview of the discussions held and conclusions drawn from the workshop. It captures the insights and shared practices presented during the workshop, reflecting both the diversity of approaches adopted by member countries and the common challenges encountered. Special thanks and appreciation go to the participants in providing their expertise and collaboration in this important exchange. The WGELEC has decided to continue the exchange of experiences regarding the systems, and to initiate new activities if a need is identified.

This report was approved by the NEA Committee on the Safety of Nuclear Installations (CSNI) at its 70th Session on 8-9 December 2021 (NEA/SEN/SIN(2021)2/REV, not publicly available).

Informed by the outcomes of the workshop, this report summarises the range of experiences and insights shared by participants, with the aim of informing continued good practice in managing OPCs in nuclear power plants.

List of abbreviations and acronyms

AC	Alternating current
AGR	Advanced gas cooled reactor
CSNI	Committee on the Safety of Nuclear Installations (NEA)
CT	Current transformers
GIS	Gas insulated switchyards
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HV	High voltage
ICC	Independent core cooling system
IEC	International Electrotechnical Commission
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (United Kingdom)
OPC	Open phase condition
PWR	Pressurised water reactor
ROBELSYS	Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident
RSK	Reactor Safety Commission (Germany)
SEPAM	Class 1E qualified protective relays
SST	System service transformer
TSO	Transmission System Operator
WGELEC	Working Group on the Safety of Electrical Systems (NEA)

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Executive summary

An open phase condition (OPC) is defined as an open circuit of one or two of the three phases of any power circuit needed for the normal operation of electrical systems. It is a recognised phenomenon that may compromise the operational capability of electrical power systems of nuclear power plants. Operating experience has shown that OPCs may be difficult to detect with existing plant instrumentation and electrical protection schemes under certain operational conditions, and there is the potential for severe voltage imbalance, resulting in unintended operation or failure of electrical equipment. In some cases, the inability to detect and disconnect the unbalanced electrical voltage from the safety bus prevented transfer to a standby off-site power supply or standby alternating current (AC) power source.

The 2014 NEA workshop on the Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident (ROBELSYS) identified that the OPC phenomenon affected several nuclear power plants around the world. However, there was little common understanding of the effects or how to detect and manage the issue. Participants in this workshop, including a number of active members of the NEA Working Group on the Safety of Electrical Systems (WGELEC), collaborated with the IAEA to develop the IAEA Safety Report Series No. 91 entitled “Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants” (NEA, 2016a).

The establishment of the NEA’s WGELEC coincided with the drafting of the IAEA Safety Report Series No. 91 (SRS-91), when methods for detecting OPCs were still under development. While SRS-91 identified some early possible solutions, there was little experience with their deployment or use and therefore it was too early to provide any definitive advice on suitable solutions.

Since the publication of SRS-91, measures have been designed and implemented at many nuclear power plants. Both the IAEA and NEA have long recognised the benefit in exploring how plant designers, operators and regulators have managed this topic. To build on this, an IAEA-NEA joint workshop for OPCs was undertaken in 2020, bringing together member countries to discuss and compare various measures put in place, and to identify any difficulties encountered during development or deployment, as well as best practices, where possible.

Workshop presentations and discussions confirmed that the challenges in developing and implementing detection methods, as outlined in SRS-91, were encountered in practice. Following the events which initiated the development of SRS-91, many regulatory authorities revisited their regulations or highlighted to licensees the importance of addressing such design vulnerabilities in electric power systems. This has been achieved by updating existing regulations or publishing new regulations or technical positions with the aim of providing technical bases and criteria for protecting the plant electrical power systems from the unwanted consequences of unbalanced electrical voltages, which can prevent the safety functions of electrical power systems from performing as required. The industry followed regulatory requirements by providing different technical solutions. Because many different configurations of the off-site and on-site electrical power systems exist, the specific technical solutions were designed to reliably detect and disconnect the electrical equipment for the unbalanced electrical voltage. A combination of automatic and manual actions was observed in various technical solutions. This has often been based on the outcome of analysis identifying the need for prompt action and the desire to avoid spurious operation of sensitive protection settings.

The experience of the participants has shown that implementing solutions requires careful consideration of both the placement of protection devices within the system and the protection settings to balance safety requirements with the need to discriminate faults under all operational conditions. It was noted that qualifying modern protection relays remains a challenge, although guidance exists from both the IAEA and International IEC standards.

It was therefore the conclusion of the workshop participants that the information and guidance provided in SRS-91 considers all these aspects and has been sufficient to support the development of measures to detect and take appropriate action against OPCs. The member country participants at the workshop did not highlight any additional difficulties with implementing measures but considered it timely to have reviewed the various approaches taken to ensure that no additional techniques and measures could be considered.

It is considered that SRS-91 continues to provide appropriate advice to nuclear power plants on the risks and management of OPC and there is no reason to review its content at this time.

1. Introduction

1.1. Background

An open phase condition (OPC) is a known phenomenon in the power industry and is recognised as having had an adverse impact on the electrical power systems of several nuclear power plants. An OPC may challenge plant safety systems. Operating experience in different countries has shown that currently installed instrumentation and protective schemes have not been adequate to detect this condition and initiate appropriate action.

An OPC may occur as a result of various faults, including circuit breaker poles not opening or closing, or the failure of transformer bushings or line insulators, leading to a loss of circuit continuity. This type of fault creates voltage and current imbalances in electrical power systems that may be detrimental to operating equipment. An OPC, if not detected and disconnected in a timely manner, represents a design vulnerability for many nuclear power plants. It may lead to a condition in which neither the off-site power system nor the on-site power system is able to support the safety functions.

An OPC that occurs in a plant with equipment important for safety supplied from a common power source can result in the degrading or tripping of redundant equipment, thereby compromising the overall safe shutdown capability of the plant.

The NEA ROBELSYS[1] workshop in 2014 (NEA, 2015) identified that the OPC was a phenomenon that had affected a number of nuclear power plants around the world but for which there was little common understanding of the effects or how to detect and manage the issue. Participants in that workshop worked with the IAEA to initiate development of the IAEA Safety Report Series No. 91 on Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants or SRS-91 (IAEA, 2016a).

SRS-91 was written with several active members of the NEA's WGELEC (Working Group on the Safety of Electrical Systems). The writing of the SRS-91 coincided with the establishment of the NEA WGELEC, when techniques were still being developed to detect OPC. Therefore, while SRS-91 identified some early possible solutions, there was little experience with their deployment or use and therefore it was too early to provide any definitive advice on suitable solutions.

Since the publication of SRS-91, measures have been designed and implemented at many nuclear power plants. Both the NEA and the IAEA have long recognised the benefit in exploring how plant designers, operators and regulators have managed this topic.

The NEA WGELEC and the IAEA agreed that discussing and comparing the measures put in place to manage OPCs, and any difficulties encountered during their development or deployment, could promote knowledge and nuclear safety. To identify where possible good practices by widening the scope of participation, a joint NEA–IAEA workshop (hereafter referred to as "the workshop") was organised on 27–29 October 2020 as an online event.

1.2. Objective

The objective of the workshop was to follow up from the experiences identified in IAEA SRS-91 and capture the various practices and design provisions regarding OPCs that have

[1] Robustness of Electrical Systems (ROBELSYS) was a continuation of the DIDELSYS Task Group.

been implemented to upgrade existing plant designs in addition to highlighting any difficulties that have been encountered with their implementation.

1.3. Scope

The workshop was mainly devoted to discussing and comparing the measures that have been put in place and any difficulties encountered during their development or deployment, identifying, where possible, good practices. The workshop discussions specifically included the:

- identification of measures developed to detect and mitigate OPCs;
- sharing of experiences gained in the development and operation of such systems in the detection and operation of these measures;
- identification of any good practices in the development and operation of these measures.

1.4. Structure

This publication comprises three main sections and two appendices, as follows:

- Section 1 introduces the background, objective, scope and structure of the publication.
- Section 2 provides the overall status of the international activities and publications to improve the robustness of nuclear power plants to OPCs, as well as the lessons that were learnt from the OPC events.
- Section 3 provides a summary of the workshop presentations.
- Section 4 provides an analysis of the workshop based on participating countries' presentations.
- The technical meeting agenda is included in Appendix I.
- Appendix II, which provides PowerPoint presentations given at the workshop, is made available upon request by the NEA by emailing the contact person indicated on the website of WGELEC: www.oecd-nea.org/jcms/pl_25383.

2. Overall status

2.1. IAEA activities and publications to improve safety of electrical power systems

The IAEA has implemented a number of activities that have involved the consideration of specific electrically related issues at nuclear power plants across the world. It has revised a number of safety standards, including the following:

- IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design (IAEA, 2016b);
- IAEA Safety Standards Series No.SSG-34, Design of Electrical Power Systems for Nuclear Power Plants (IAEA, 2016c);
- IAEA TECDOC-1770, Design Provisions for Withstanding Station Blackout at Nuclear Power Plants (IAEA, 2015a).

The Safety Reports Series No. 91, Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants (SRS-91) (IAEA, 2016a) covers relevant aspects of OPCs initiated in the transmission systems or on-site plant electrical systems. It provides details on the methods that can be used to identify vulnerability to OPCs in existing electrical protective schemes. The technical guidance provides technical options to address the OPC vulnerability and thereby enhance the safety of nuclear power plants. The publication serves as a useful guidance for all personnel involved in the design, manufacture, qualification, operation, maintenance, management and licensing of nuclear facilities.

2.2. NEA activities to improve robustness of electrical power systems

The NEA has published several reports to resolve specific issues which have affected electrical systems, including those identified after the Forsmark-1 event and the Fukushima Daiichi accident. They have included the following:

- NEA/CSNI/R(2009)10, "Defence in Depth of Electrical Systems and Grid Interaction" (NEA, 2009);
- NEA/CNRA/R(2011)8, "Status of OECD/NEA Country Regulatory Responses to the Forsmark-1 Event of 25 July 2006 and NEA/CSNI DiDELSYS Task Group Report Recommendations" (NEA, 2011);
- NEA/CSNI/R(2015)4, Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident (ROBELSYS) (NEA, 2015).

The main purpose of the ROBELSYS activity was to improve the robustness of nuclear power plant electrical systems and defence in depth by comparing design practices, plant emergency and operating procedures in member countries. It has long been recognised that the safety review process of nuclear power plant electrical systems can be improved by learning from best practices in member countries and that the co-operation among member countries to improve safety can be promoted.

Following the ROBELSYS workshop, the NEA Committee on the Safety of Nuclear Installations (CSNI) established a permanent Working Group on the Safety of Electrical Systems (WGELEC) in 2016.

The WGELEC aims at improving international understanding on the issues which can lead to challenges to the functionality of equipment relying on electrical power systems, as well as at sharing good practice techniques to prevent, detect and mitigate such events. Plant operators, designers and national regulators, together with the IAEA, participate in the WGELEC activities.

2.3. Significant OPC events that shaped the sector

In 2012 at Unit 2 of the Byron Nuclear Power Plant (NRC, 2012a), a design vulnerability in the protection scheme of the electric power system prevented the detection of the loss of a single phase between the transmission network and the on-site power distribution system, resulting in:

- unbalanced voltage conditions at redundant safety buses (due to a degraded off-site power supply);
- tripping of operating equipment, such as essential service water pumps, centrifugal charging pumps and component cooling water pumps;
- prevention of the on-site electric power system from supplying plant safety systems.

This loss of a single phase resulted in a condition in which neither the on-site nor the off-site electric power system was able to perform its intended safety function (i.e. to provide electric power to the safety buses with sufficient capacity and capability to permit the operation of structures, systems and components important to safety) until the operators diagnosed the problem and disconnected the degraded off-site source.

In Unit 1 at the Byron Nuclear Power Plant (NRC, 2012a), a failed insulator in the 345 kV off-site power system resulted in a single OPC with a phase to earth fault on the transmission side of the standby transformer circuit. In this event, the fault current was high enough to actuate protection schemes on the 345 kV system. The safety buses experienced a loss of voltage condition after 345 kV system breakers disconnected the off-site power source. Both standby AC power sources started and energised the safety buses as designed.

The event in Unit 3 at the Forsmark Nuclear Power Plant (IAEA, 2015b), on 5 May 2013, showed that the failure of one pole of a 400 kV circuit breaker to open and disconnect the power source from the switchyard caused a double OPC, creating an unbalanced voltage condition. This was not detected by the existing instrumentation or electrical protection scheme owing to low load conditions and, as a result, the electrical protection scheme did not disconnect the safety buses from a faulty electrical system. As a consequence of the OPC, cooling of the spent fuel pool and cooling of the emergency diesel generators was lost until manual action by the plant operators disconnected the power supply from the 400 kV switchyard. After the supply from the off-site grid was disconnected, the cooling systems were manually restored, enabling standby AC power source-supplied power to the safety buses until the OPC in the 400 kV switchyard was resolved and the off-site power from the 400 kV switchyard was restored.

The majority of OPCs in the nuclear power plant operating experience are events that occurred on the high voltage side of the unit transformer or standby transformer. There is one known OPC event in the on-site power system that occurred due to a maintenance error. In this case, the standby AC power source generator breaker did not close properly in all poles, resulting in the failure of one phase. This fault was considered a single failure which impacted one safety train only.

Table 1 of SRS-91 (IAEA, 2016a) provides examples of events with open phase conditions that occurred between 1994 and 2014.

2.3.1. Open phase condition failure mechanism

An OPC in a three-phase power system typically results in an unbalanced voltage condition. Continued operation for an extended duration with unbalanced voltage conditions can damage equipment as a result of overheating and vibration, or result in the inadvertent trip of electrical equipment and cause a plant transient. If more than one train of equipment is supplied from a common power source, the unbalanced voltage conditions can result in damage to redundant equipment important to safety. There is a risk that operators may not be able to respond in a timely manner to prevent damage to multiple pieces of equipment due to a lack of information available from existing measurements, indications and automatic actions.

The operational configuration of the plant or the off-site power source (e.g. switchyard breaker configuration) may result in the condition remaining undetected until:

- the plant loading changes by removing or connecting loads;
- the off-site power source is reconfigured through switchyard breaker operation; or
- a performance abnormality such as load tripping occurs.

If the voltage imbalance levels are low as a result of the type of fault or transformer winding configuration and earthing, then the degraded conditions can go undetected for a long period of time and may not be identified until the transformer load is increased due to a change in the plant alignment such as plant shutdown or start-up.

2.3.2. Proposed solutions in SRS-91 to manage open phase conditions

SRS-91 (IAEA, 2016a) suggested that each plant evaluates permanent corrective solutions to diagnose and respond to an OPC. These solutions could be based on an on-line detection scheme to provide a prompt identification of an OPC on off-site power sources.

The design of detection and protection schemes, and any automatic or manual actions, are subject to plant-specific evaluation of the consequences of an OPC. To ensure correct operation of the electrical equipment (safety and non-safety), the capability to withstand an OPC needs to be taken into account when selecting set points. The new protective measures need to be co-ordinated with any existing protection schemes.

In general, an OPC is not postulated to occur on multiple off-site or on-site circuits simultaneously but it has to be considered whether the grid configuration could allow a single OPC to affect more than one off-site power source simultaneously.

SRS-91 indicated that the preferred solution would be to detect an OPC on the low voltage side of any transformers associated with the off-site power sources since this enables OPCs on both the high and low voltage sides to be recognised. However, plant-specific analysis may identify that not all OPCs can be detected from a single location, especially when a transformer is lightly loaded or unloaded. A combination of detection schemes on the high voltage and low voltage sides of the transformers may facilitate a comprehensive solution for all plant operating conditions and plant configurations.

The design of the protective system needs to consider disconnecting only the power source affected by the OPC in accordance with the defence in depth concept.

The testing requirements need to be commensurate with the safety classification of the OPC detection scheme.

Actuation logic

The actuation logic of the implemented permanent solutions may depend on the protected area and plant load. For example, if a transformer is in standby mode, without a load, an alarm is activated, indicating an OPC in the affected off-site power source. The OPC, in this case, does not affect any downstream equipment; therefore, the operating personnel have some time to cope with the OPC. If the transformer is in service mode with a load, an alarm is activated, indicating that the OPC is in the affected off-site power source. The time to respond to an OPC needs to be evaluated on a plant design basis.

Some plants may conclude that automatic disconnection is not necessary because manual actions are fast enough to prevent impairments of equipment important to safety. Where necessary, automatic actions (e.g. disconnection, switchover activation/inhibition) ensure that operating equipment is not exposed to an OPC for an extended duration. The alternate off-site or on-site source is then automatically aligned to maintain plant safety.

Solutions on the high or low voltage side of the transformer

Where a permanent protective solution is considered, it will likely involve the measurement of one or more of the following parameters (see examples in Appendix II):

- negative sequence voltage;
- negative sequence current;
- magnetisation current;
- zero sequence current;
- zero sequence voltage;
- current injection;
- phase to phase or phase to earth voltage (properly set for unbalanced conditions due to an OPC).

The above list is not comprehensive. Other measurements or combinations of the above measurements can be used as well.

3. Summary of the workshop

3.1. Management of the workshop

This event was originally planned as an in-person meeting at the IAEA offices in Vienna, Austria. However, due to COVID-19 restrictions, it was decided to organise the meeting as an online meeting. The workshop agenda was adapted to three half-day sessions to allow participants to join from countries across many different time zones.

In total, 57 participants from 20 countries attended the technical meeting. The participants were composed of staff members of regulatory bodies, nuclear power plant operators, utility organisations, design and engineering consultant organisations, as well as of international organisations engaged in activities related to nuclear power plant safety and regulation. In addition, many of the contributors to the original SR.91 participated.

In addition to an opening session, the workshop included 17 topical presentations organised in two thematic areas of industry activities and regulatory positions on OPCs.

Discussions after the presentations enabled participants to explore in more detail the experiences and problems that had been experienced as analyses and schemes were implemented. An important aim of the meeting was to ensure that the practices of the participating countries or standards developed by other international organisations were identified and assessed for appropriate application.

3.2. Opening session

The opening session included welcome addresses by representatives of the IAEA and NEA. The session was further complemented by keynote presentations on the importance of the technical meeting's overall theme.

The topic of each technical session was introduced by the chairperson responsible for each technical session.

The Chair of WGELEC introduced the WGELEC objectives and activities; the WGELEC inputs to other international activities through members of the group that includes the application of IAEA safety standards and development of related technical reports; and the development of IEC[2] standards on electrical power systems.

He noted that the WGELEC mission is to advance the current understanding and address safety issues related to electrical systems of nuclear installations with the aim of making significant contributions towards three goals:

- enhancing the robustness of electrical systems;
- enhancing the analysis and simulation of electrical systems;
- addressing safety challenges from the use of power and software-based electronics in electrical systems.

The WGELEC scope covers:

- All equipment located within a nuclear installation including:
    - emergency power systems, generators, cables, switchboards, transformers, breakers, batteries, protective relaying;

[2] International Electrotechnical Commission, a standard development organisation

  - instrumentation and control equipment specifically needed to manage this electricity supply function;
  - loads supplied (e.g. motors, drives, sensors, relays, computers), but only regarding their electrical characteristics.

- Safety aspects ranging from issues specific to a given type of equipment up to considerations regarding the overall behaviour of a nuclear installation's electrical power system.
- Two key areas of focus:
  - existing reactors and fuel cycle installations;
  - applicability for new installations, in particular advanced reactor designs.

Furthermore, the Chair of WGELEC informed the participants of the progress of Activity 6 – Experience with OPCs, noting that six years had passed since OPCs had been raised during the ROBELSYS workshop. This led to the development of IAEA SRS-91 and many countries have developed approaches and implemented detection systems.

The Chair noted that the aim of the workshop was to:

- identify measures developed to detect and mitigate OPCs;
- share experiences gained in the development and operation of such systems in the detection and operation of these measures;
- identify any good practices in the development and operation of these measures;
- identify opportunities for future research where technical gaps exist in current technology.

Output will be reported through an NEA report on proceedings. The Chair concluded by presenting six activities launched by the WGELEC:

- early identification of electrical failure mechanisms that affect safety at nuclear facilities;
- identification of good practices for advancing electrical power system robustness in case of deviation from their normal operating conditions;
- comparison of methodologies for simulation of electrical systems;
- establishment of measures against accelerated degradation of batteries and failure of batteries that affect safety at nuclear facilities;
- new devices for electrical equipment replacement/retrofit and new build;
- experiences with the solutions implemented to identify and manage OPCs.

3.3. Industry activities

This session comprised eight topical presentations, scheduled in two half-day sessions, covering the industry activities on OPCs. A synopsis of each of the presentations is provided below.

3.3.1. Co-ordination of unbalance protection: Summation of all information into a co-ordinated protection scheme, by Mr Magnus Knutson (Sweden)

Mr Knutson was the technical lead for the development of the SRS-91. In his presentation he introduced topics presented in SRS-91, describing the history of OPC, the earlier approach to overcurrent co-ordination - selectivity diagram, relay protections for shunt faults (short circuits) and existing (before Byron-OPC) relay protections for unsymmetrical conditions. He provided examples on how to co-ordinate negative sequence current and voltage protection in the same chart:

- Some protection relays measure unbalanced current, other protection relays measure unbalanced voltage, but both need to be co-ordinated and presented in the same scheme.
- A good approximation for the translation between negative sequence voltage and negative sequence current is for:
  - synchronous generators: negative sequence reactance;
  - asynchronous motors; starting current ratio.
- Assuming transformer voltage ratio and negative sequence voltage drop cancels out, the voltage unbalance is constant through the whole electrical power system downstream the OPC.

Furthermore, he described new OPC relay protection, which includes:

- alarm (Io) in transformer neutrals for very small unbalances;
- alarm (U-) on safety bus;
- low set-value, long time;
- tripping (U-) safety bus.

In a summary, he highlighted that a co-ordinated protection system should provide for coping with all kinds of unbalance regardless of loading, fault type, fault location, protecting, tripping and alarming the electrical equipment in a predetermined selective way.

3.3.2. Behaviour of the Spanish nuclear power plants in relation to the OPC, by Mr Carlos Martinez Sánchez (Spain)

Mr Martinez Sánchez presented the current actions implemented at Spanish nuclear power plants to cope with OPC, which include three stages. During the first phase, which was finalised in 2016, the OPC analysis was performed at all nuclear power plants. The second stage involved implementation of actions identified in a previous stage, and the third phase focused on implementation of technical solutions, specific to each nuclear power plant site. Solutions include motor protection, OPC detection on power supplies, and improvements of human system interfaces to inform operators on a detection of OPC at the main control room.

In summary, all Spanish nuclear power plants have installed OPC detection systems. Different solutions have been adopted by each utility. All plants have carried out a monitoring stage of the system. A trip automation, which will be implemented, includes the following characteristics:

- four out of five nuclear power plants have initial plans to automate trips based on the OPC detection systems;
- one nuclear power plant has indicated that it will only implement alarm.

This solution is in accordance with national requirements (NRC, 2012b).

3.3.3. Analysis and corrective actions implementation for OPC and unbalanced voltage in the high voltage external network of the Belgian nuclear power plants, by Mr Raphael Renard (Belgium)

Mr Renard presented a study case with a single line diagram, simulation results of OPC and required modifications in electrical scheme, and examples of technical solutions at a Belgian nuclear power plant. The study case involved simulation of OPC at different electrical buses, e.g. two safety levels by divisions supplying loads for accident conditions (LOCA, MSLB), and an electrical bus dedicated to externally induced natural or human induced events (e.g. airplane crash, tornado). Furthermore, he highlighted that discussions with the Transmission System Operator (TSO) of the Belgian high voltage electrical network has been undertaken to assess what situations are likely or not to happen, such that the steady unbalanced voltage on one external power supply of a plant is unlikely (except for a situation similar to OPC close to the plant), steady unbalanced voltage on both external power supplies are considered extremely unlikely, and open phase without earth fault undetected at the grid side is considered unlikely.

The OPC analysis resulted in several recommendations ensuring that the generator will trip before all the motors in case of external unbalanced voltage (negative phase sequence current); voltage protections are based on a three-phased measurement in all plants; busbar unbalanced voltage supervision is implemented where it does not exist; modifications are made to the switchboards supplies control, motors protections, switchover and diesel generator automatism to ensure a safe power supply without motors trip; and the supervision of the secondary voltage of the RAT is implemented to prevent transfer in case of unbalanced voltage on the 150kV network.

In conclusion, it was determined impossible to prevent an islanding or a trip of the nuclear power plant if the high voltage network is not healthy. However, grounding of the high voltage neutral of a transformer has a significant impact on the detection and on the consequence of an OPC on the high voltage external network. Solutions to cope with OPC were fully implemented only when a suitable qualified protection relay was available. Different solutions have been implemented to fit the existing configuration of the plant. In case of OPC or unbalanced voltage conditions, it is possible to reach a cold shutdown state in a safe way for all the Belgian nuclear power plants.

3.3.4. Forsmark 1-3 measures to manage OPCs, by Mr Albert Nilsson (Sweden)

Forsmark has experienced electrical disturbances in recent times, which required finding the root causes. These disturbances were within the design-basis envelope; however, they caused unwanted and unexpected consequences for the safety systems. The disturbances were caused by different phenomena, such as OPC and lightning. A systematic analysis was performed to address these electrical disturbances.

The analysis method involved the identification of (potentially dangerous) electrical phenomena, evaluation of what phenomena could be initiating events, bounding values and event frequencies for all identified initiating events for which the IAEA Safety Guide SSG-34 on design of electrical power systems for nuclear power plants (IAEA, 2016c) was a good inspiration.

As a result of the analyses, measures were taken to address unbalanced voltage, such as the installation of a quality electrical protection device; revisiting the protection concept for fast transients that are too fast to detect and disconnect (passive protection surge arresters); and updating the generator overvoltage protection settings.

In conclusion, Mr Nilsson highlighted that a systematic approach is needed to address unbalanced voltage; transparent equipment with adequate endurance is required to validate safety functions and error mode effects; and sensitivity analyses are required to determine the plant robustness and the acceptable level of diversity.

3.3.5. Implementation of measures to open phase in Doel Nuclear Power Plant, by Mr Dirk De Win (Belgium)

Mr De Win presented several cases of how an OPC event is detected and managed in electrical power systems. He addressed the following topics: Class 1E open phase and unbalanced voltage protective function, open phase and unbalanced voltage relay design basis and status open phase and unbalanced voltage protection.

The analysis of OPC included cases where it was caused by a broken line, breaker failures, or an event which causes voltage irregularities, and unbalanced voltage caused by various events including open phases, breaker failures, grid unbalance and auxiliary system unbalance.

A study performed by Tractebel Engie showed that if the main generator is disconnected, an unbalanced voltage on the primary side of the step-up transformer will not lead to unbalanced voltage on the nuclear power plant network. This is due to the neutral connection of the high voltage side of the transformer. If the main generator is connected and with initial settings, motors are tripped by unbalanced current protection for open phase conditions before the generator trips. When the main generator is connected and with initial settings, the generator may not trip in case of unbalanced voltage on the high voltage network, which is not acceptable for nuclear safety.

An open phase and unbalance voltage relay provides protection against loss of safety function due to unbalanced voltages at the safety buses, including upstream open phase events, including both in plant and transformer open phase events, as well as for every source alignment during normal power operation or shutdown. The Class 1E open phase and unbalanced voltage protective relays utilise existing protection circuits (generator protection relay in normal operation), existing logic circuits (trip offsite power and island operation). The qualified Class 1E relay Schneider Type SEPAM Relay (for negative sequence detection on 6 kV or 6,6 kV boards) has been used due to experience with similar relays for various protective functions.

A protection concept is based on Class 1E qualified protective relays (SEPAM) installed on each train for automatic detection of an abnormal voltage unbalance, which affects the Class 1E equipment and provides an alarm to the main control room, automatic detection and disconnection from an unbalanced electrical voltage, and automatic start of a diesel sequence of an alternate (bunker) power source in both operation and shutdown modes.

All unbalance voltage protections were implemented in 2018-2020 during plant outages. Operating procedures were modified to provide sufficient guidance to recognise and to respond to OPCs. Unbalanced grid voltage compensatory actions were incorporated in the operator simulator training. Finally, the maintenance and inspection strategy of transformers and high voltage grids included visual checks, thermography and measurements.

3.3.6. Open phase analysis at Cernavoda Nuclear Power Plant and measures to mitigate its effects, by Mr Liviu Matescu (Romania)

Mr Matescu presented a study of OPCs to analyse possible vulnerabilities, stresses in the support insulators for different electrical system configurations and existing electrical protection schemes. The study of OPC revealed that an OPC fault has a very low probability because of the robust high voltage interconnection system (using flexible conductors and oversizing connection components yielding high safety coefficients). Most of the scenarios that were considered for an OPC fault are covered by the existing transformer/generator protections. For the scenarios where there is no protection in place, the individual loads are properly protected by their own protection systems. With this regard, modifying the existing protection system to account for OPC faults is not recommended because it is covered already by a complex protection system.

3.3.7. Development of grid open phase detection & safety case strategy in the United Kingdom, by Mr John Reilly (United Kingdom)

Mr Reilly started his presentation with a description of the OPC event that occurred in Dungeness B in 2014 when a single OPC in a 400 kV transmission system breaker resulted in an automatic main generator trip and manual transfer of station supplies to on-site essential and backup diesel generators. This event has been included in the SRS-91.

The effects of phase imbalance faults on the safety case for all nuclear power plants have been studied. Phase imbalances may compromise the electrical power systems, so the safety case must include details that:

- help the operator understand how difficult the fault condition can be to detect, how they can diagnose it and then minimise the interruption to electrical supplies;
- make the operator aware that tripping of operating equipment could occur, and that essential plant equipment required for post trip cooling could also be compromised;
- identify and ensure that electrical equipment that has tripped on thermal overload will have time to cool down before being reset and restarted;
- highlight that failure to diagnose a phase imbalance and disconnect from the degraded supply will prevent the backup power systems from starting.

In essence, phase imbalance faults undermine the existing safety case claims of reliable electrical supplies being available during all operational modes.

A phase imbalance programme was set up to control the development of the alarms and safety case work that summarised the optioneering process, set out the requirements for the alarms, enabled the design work to go ahead in advance of the safety case updates and supported reducing the risk from phase imbalance as soon as practicable. An enquiry specification was developed and a tender process completed to select the preferred design house. As of the presentation, the implementation status included a design substantiation of electrical protective devices, equipment qualification, procurement of the panels, protection relays and current transformers, manufacturing of the assembled panels, testing of the final design, delivery of all equipment to sites, development of the installation documentation and trial installation and testing. Five out of the seven advanced gas cooled reactor (AGR) stations had installed the phase imbalance alarms, with the final two due to complete in 2021. The installation of a similar alarm at the one pressurised water reactor (PWR) station, Sizewell B, is an enhancement to an existing system, and was planned to be installed in 2022.

3.3.8. Open phase condition update Bruce A Unit 1, by Mr Jeff Stevenson (Canada)

Mr Stevenson made this presentation together with Bendong Sun and Dahir Haji Mohamed from Bruce Power. They presented a review of an OPC event at Bruce Power, the solution to OPC detection, the engineering analysis performed, a a conceptual engineering and detailed design of OPC protection.

The OPC event that occurred at Unit 1 of Bruce involved a single OPC in the 230 kV side of the system service transformer due to a broken drop lead connection to the system service transformer. Existing protection did not detect this during light load conditions, maintenance cooling pump tripped on unbalance protection, standby pumps started and tripped again, operators had no indication of an issue with the electrical supply, and OPC was identified when operators started a larger pump. Unit loads transferred to an alternate supply and cooling was restored. This event was included in SRS-91 (IAEA, 2016a).

A set of analyses were conducted to quantify the response to the electrical distribution system when open phase faults occur. Conceptual engineering of OPC protection considered several options, such as: installation of the new high sensitivity current transformers and protection relays monitoring high voltage (HV) currents; installation of alternative analysis schemes such as active detection using signal injection; use of existing current transformer and off the shelf relays; use of existing revenue metres for open phase detection; and, finally, doing nothing if the existing design is sufficient.

The solution for OPC detections involved the development of a redundant open phase detection using an existing revenue meter scheme for each system service transformer (SST) with separate alarms to the control room and minimum field modifications (e.g. using existing equipment, and adding blocking switches to block alarms during metering maintenance). Open phase detection was installed at all Bruce A SSTs and did not require outages. The installation of open phase detection at Bruce B is in progress.

3.4. Regulatory positions and activities

This session was comprised of seven topical presentations, scheduled over a half day, covering the regulatory positions and activities on OPCs. A summary of each of the presentations is provided below.

3.4.1. Coping status for the OPC in Korea, by Mr In Jun Hwang (Korea)

Mr Hwang presented the status of actions for coping with OPC in Korea. He noted that a review of design vulnerability to OPC had resulted in immediate actions at operating nuclear power plants, field inspection for robustness of electrical design and OPC protection. Inspections of operating nuclear power plants resulted in recommendations, issued in September 2019. These recommendations addressed a design vulnerability on the OPC detection of protection scheme of the overhead high voltage side of the 765 kV main transformer and interconnection line of the 154 kV switchyard that might cause an OPC event due to external factors. In addition, it was recommended to address a vulnerability of OPC detection design because the installed protection scheme could not detect the OPC.

Future plans for coping with OPC involved reviews of equipment improvements of off-site power systems for the OPIS installation (to be completed by 2022) and a field Inspection of Installation State and Test for the OPIS (to be completed by 2024).

3.4.2. Measures to detect open phase conditions in German nuclear power plants, by Mr Robert Arians (Germany)

In 2013, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) published an information notice on insufficiently detected failures of individual phases of grid connections in several foreign plants. This information notice contained a recommendation to consider suitable temporary measures to ensure that any unavailability of individual phases of the grid connection is detected and that the effects of OPCs on the safety system are prevented. A year later, the reactor safety commission issued recommendations to address OPCs of the main, reserve or emergency power supplies. It was recommended to detect asymmetrical voltage conditions in the three-phase system, to measure and monitor all voltages in the mains connections and, to protect against interference from asymmetries, an additional protection for the detection of an unbalanced load should be installed.

Furthermore, the unavailability of the standby grid connection or the emergency power grid due to OPCs must be detected so that suitable measures can be taken, and the unavailability of the main power supply due to OPCs after normalisation of the main power transformer (e.g. after maintenance) must be detected before switching back the auxiliary power to the main power supply. Due to the potential for cross-redundancy failures of safety equipment, it is necessary to install equipment that reliably detects OPCs so that cross-redundancy failures of safety equipment cannot be caused.

The reactor safety commission (RSK) and GRS issued several "early" recommendations concerning the detection of OPCs and to also implement a suitable monitoring of the external grid connections and emergency power busbars. All German nuclear power plants in operation at the time had implemented measures for detection of OPCs. Due to the different constellations inside the plants, there were large differences in the implementation of these measures from plant to plant. Used devices are not nuclear-qualified, but several different (diverse) devices are used to increase the reliability in detecting faults and to reduce the probability of false alarms.

3.4.3. Regulatory action for OPC potential at nuclear facilities in Japan, by Mr Kazuyoshi Kataoka (Japan)

Following an OPC event at the Byron Nuclear Power Plant, the Technical Information Committee of the Nuclear Regulatory Authority (NRA) determined US NRC BL2012-01 "Design vulnerability in electric power system" as "Technical Information requiring regulatory action". The NRA issued a request to every licensee to analyse their electrical power systems for any potential OPC vulnerability. It was determined that OPC events have never been experienced and the likelihood of an OPC occurrence was deemed negligibly small in nuclear power plant switchyards in Japan. Nevertheless, operational measures were required for some of the transformers that could not detect an OPC with existing protection relays.

Many Japanese nuclear power plants are equipped with high voltage gas insulated switchyards (GIS), which are not susceptible to OPC events. For those nuclear power plants which have an open-air switchyard with overhead lines, the protection for an OPC was investigated. In 2014, the Nuclear Regulation Authority (NRA) amended regulatory guides that clarified regulatory requirements ensuring power supply, such as to detect any damage, failure or other abnormal conditions of components and to prevent their escalation, even if an OPC occurs. A detection of degraded offsite power and the isolation of the failed section should be executed or the standby emergency bus (manual operation might be allowed) should be switched to.

Licensees developed and successfully tested three types of protection systems, including two new OPC detection systems that consist of digital relays and optical current transformers (CT) installed at the primary side of the transformer. Automatic detection and manual isolation action are performed according to validated manual isolation procedures.

In 2020, the NRA conducted an open hearing with the licensees to follow up on the implementation of the OPC measure installation plans at nuclear power plants.

3.4.4. ONR expectations on measures to manage OPC at existing facilities and new reactors, by Mr Kevin Pepper (United Kingdom)

Mr Kevin Pepper presented a summary of events in the United Kingdom, about how the Office for Nuclear Regulation (ONR) expects an open phase event to be considered by a licensee, and how this is being reflected in work by licensees and Generic Design Assessment requesting parties.

As of the presentation, there had been four recorded events involving OPCs. All were the result of failures with offsite transmission network equipment. Based on experience, ONR considers an OPC to be a frequent fault (probability $>10^{-3}$ per annum), i.e. not something that can be completely prevented from affecting a site. With this regard, ONR expects that licensees analyse the consequences of an OPC on systems important to safety. Where licensees can demonstrate that even under an OPC the site can continue to operate as designed, no design measures may be necessary. Where licensees identify that systems important to safety may not perform as anticipated (such as due to voltage distortion), preventative measures are required. Since it is considered a frequent fault, ONR expectations are for two lines of protection.

Where the analysis identifies that a fault will impact on systems important to safety in a short period of time (typically less than 30 minutes), a safety system should be initiated automatically. While an OPC can be difficult to detect under certain situations (such as an unloaded standby transformer), the expectation is that the fault should not exist unrevealed. Only where no means of continuous detection of the fault is reasonably practicable should periodic testing be considered, and this should be justified in the safety case.

ONR has maintained an oversight of the work done by nuclear site licensees in the United Kingdom through interactions with licensee technical teams and site inspections. The work done by EDF Energy for their sites was presented at this workshop. ONR has also ensured that new reactor designs going through the Generic Design Assessment process have considered OPC as part of their safety cases.

3.4.5. Regulatory perspectives on the management of "Degraded Power Supplies" in nuclear power plants, by Mr Mattias Karlsson (Sweden)

Mr Karlsson presented an overview of the Swedish regulatory perspective on OPCs, which are considered a subset of the broader issue of Degraded Power Supplies, covering regulatory activities on a national as well as an international level to address the topic.

The works initially started in 2013 after the Byron and Forsmark open phase events. Historical events in the electrical power supplies were reviewed and two main groups of transients were identified: 1) phase unbalance (e.g. as a consequence of OPC) and 2) fast overvoltage transients (such as in Forsmark 2006). A number of insights into system characteristic behaviour could be derived from this and a least common denominator was sought to identify possible approaches to generically enhance electrical power system robustness and resilience. The least common denominator was defined as "unidentified degrading conductive disturbances".

The terminology was developed similarly to the IAEA plant state terminology and a comparison was made. The approach to identify practicable measures thus considered plant behaviour in the different plant states, which consequentially put the focus on plant and system design characteristics and behaviours. Various design approaches were identified through national (mainly ENERGIFORSK) and international (mainly NEA) co-operation to gather any available experiences and a few relevant works were mentioned in the presentation. The main conclusions from the NEA WGELEC report on advancing the robustness of electrical systems (NEA, 2023) were also presented, which showed that there is no consistent approach internationally to manage degraded power supplies, but some design variations of electrical power systems exist which could be studied further.

Finally, the main design changes by the Swedish licensees were summarised. Open phase detection systems have been installed at all plants, with some variations in implementation (analogue/digital, safety/non-safety) to manage OPCs specifically. Additionally, the independent core cooling system (ICC) has been enhanced to cope with a loss of interconnected electrical systems, which covers a broader range of degraded power supplies.

Three take-aways were then given to the audience: 1) The “unknown” should not be ruled out; 2) considering system properties can help (in particular when considering source, route and load both together and independently in the power supply assessment); and 3) an analysis of loss of interconnected electrical systems (and possible measures to prevent or cope with such a situation) can provide useful insights.

3.4.6. Current implementation status of measures to manage OPCs in electrical power systems of nuclear power plants, by Mr Roy Mathew (United States)

On 30 January 2012, Unit 2 at the Byron Station nuclear power plant in Illinois shut down safely after an "open phase" event. The shutdown was caused by unbalanced electrical voltage coming into the plant from the regional electric grid. This event, and others similar to it, led the United States Nuclear Regulatory Commission (NRC) and the nuclear power industry to evaluate open phase conditions. Losing one or two phases, with or without ground, on the primary (high voltage) side of a transformer connected to the transmission system can cause unbalanced voltage on the secondary (low voltage) side of the transformer, connected to plant safety equipment. If the condition is not detected, the degraded offsite power line may not be disconnected. Then, the equipment needed to safely shut down the plant may not transfer to another functioning electrical source.

The NRC alerted reactor operators to the Byron Station operating event by issuing Information Notice 2012-03, "Design Vulnerability in Electric Power System," dated 1 March 2012 (ADAMS Accession No. ML120480170). Then, on 27 July 2012, the staff issued NRC Bulletin 2012-01, "Design Vulnerability in Electric Power System," (ADAMS Accession No. ML12074A115) to confirm that licensees complied with relevant requirements for electric power systems.

The Nuclear Energy Institute (NEI), on behalf of the nuclear industry, proposed an open phase isolation system that would address the identified issue. The NRC staff sent its response, including four functional criteria that should be achieved when implementing the proposed system, to NEI on 25 Nov. 2014 (ADAMS Accession No. ML14120A203). Furthermore, the NRC staff developed Branch Technical Position 8-9, "Open Phase Conditions in Electric Power System," to provide guidance to staff in reviewing licensees’ and applicants’ proposed solutions to this issue.

As of the presentation, nuclear power plant operators were implementing the permanent solution for this issue through the installation of open phase isolation systems. These systems had been installed at most sites and were being operated in a monitoring mode to verify that the systems can adequately detect open phase conditions prior to enabling automatic actuation features. The NRC staff reviewed and agreed with the temporary measures, and regional inspectors planned to inspect the measures.

3.4.7. OPC consideration, by Mr Marcel van Berlo (the Netherlands)

Mr Van Berlo presented a solution to detect open phase conditions in the Borselle nuclear power plant. All incoming power supplies are equipment with OPC voltage detection (using ANSI 47, Siprotect device). This protection generates only alarm, no automatic action. An installation of the new protection relays (digital protection relays [Siemens Sentron 3WL - ETU76B]) at 400V buses was being investigated.

A detection of a phase asymmetry has been implemented with the following functions: a 21kV main generator is automatically disconnected and a fast transfer of house load buses to standby transformer is initiated. Should phase asymmetry be detected on transformers, the respective buses are quickly transferred to healthy off-site power source. If a phase asymmetry is detected on house load buses, which provide power supply to the safety buses, a manual transfer (disconnection of section breakers between the house load and safety bus) is made, which starts respective emergency diesel generators.

4. Analysis of workshop

Operating experience shows that OPC events continue to occur at nuclear power plants. They can be single or double OPCs, with or without a high impedance earth fault. For almost all existing nuclear power plants, the OPC was not explicitly considered in the original electrical power system analysis. Hence, the configuration of the existing instrumentation and protection schemes may not detect an OPC in a clearly defined way in all plant states. This applies especially for non-power operations, where the lower loads and lack of detection by generator negative phase sequence protection schemes make OPCs less likely to be detected.

At the time that SRS-91 (IAEA, 2026a) was written, which coincided with the establishment of the NEA WGELEC, techniques were still being developed to detect OPCs. Therefore, while SRS-91 identified some early possible solutions, there was little experience with their deployment or use and therefore it was too early to provide any definitive advice on suitable solutions.

Five years after the publication of the SRS-91, the analyses of the effects of OPCs at many nuclear power plants, together with OPC detection and mitigation measures, have been designed and implemented.

The following sections summarise the various design provisions that the industry has implemented to address regulatory positions and operating experience that involved unbalanced electrical voltage.

4.1. Following up and capturing various practices and design provisions

4.1.1. Regulatory positions/actions

The presentations showed that many regulatory authorities, following the events which initiated the development of SR91, have revisited their regulations or highlighted to licensees the importance of addressing such design vulnerabilities in electric power systems. This has been achieved by updating existing regulations or publishing new regulations or technical positions with the aim of providing the technical basis and criteria for protecting plant electrical power systems from the unwanted consequences of unbalanced electrical voltages that might prevent the safety functions of electrical power systems from performing as required. As a result, licensees were requested to analyse their electrical power systems for potential design vulnerabilities to OPC and to develop measures to resolve any identified issues. Because of the relative urgency, regulatory authorities have often requested prompt interim actions as well as implementation of corrective measures in a time-specified interval.

Although regulatory authorities have not specified the technical solutions for coping with OPCs, they have often set out that the main objective of any action should be to detect the degraded power supplies and reliably disconnect the portion of onsite electrical power systems that supply safety buses to ensure that the equipment important to safety will perform their functions as required.

4.1.2. Industry activities

The industry followed the regulatory requirements by providing different technical solutions. Because many different configurations of off-site and on-site electrical power systems exist, the specific technical solutions were designed to reliably detect and disconnect the electrical equipment for the unbalanced electrical voltage. A combination of automatic and manual actions was observed in various technical solutions. These were often based on the outcomes of analyses identifying the need for prompt action and the desire to avoid spurious operation of sensitive protection settings.

The following actions and technical solutions to detect and manage the OPC event have been implemented (or will be in the near term):

- a systematic approach to analyse design vulnerability to OPC in electrical power systems;
- sensitivity evaluation and verification analysis;
- identification of weak points in electrical power system susceptible to OPC;
- verification of the plant for lightning surge protection;
- use of simulation tools to analyse electrical power systems.

The specific design solutions for coping with OPC were identified as follows:

- a co-ordinated protection system coping with all kinds of unbalance regardless of loading, fault type or fault location;
- a system that protect, trip and alarm in a predetermined selective way;
- disconnection of the safety bus from the preferred power supply;
- modification of existing generator and bus protection relays;
- grounding of the high voltage neutral of a transformer;
- installation of qualified protection devices to detect a degraded power supply and isolate the safety bus from the unbalanced electrical voltage faults;
- improvement of operating procedures for sufficient guidance to recognise and to respond to unbalanced electrical voltage;
- improvement of operator training to understand degraded grid voltage compensatory actions;
- implementation of maintenance and inspection strategies on transformers and high voltage power supplies, including regular visual checks, thermography and measurements.

The unbalanced voltage primarily impacts the electrical equipment connected to the downstream of the open phase circuit, while the electrical equipment upstream of an open phase circuit will in most cases be unaffected. The unbalanced current, however, can affect electrical equipment both downstream and upstream of the OPC.

Finally, the measures implemented to cope with unbalanced electrical voltage have not been about protecting the equipment, but rather about ensuring the proper functionality of the required process (safety) functions in a timely manner.

4.2. Highlighting difficulties that have been encountered

When analysing a design vulnerability to OPC conditions and deciding on the best possible detection and protective solutions, the participants highlighted a number of issues. Examples of these included:

- deciding where in the electrical power systems to install an unbalanced electrical voltage protection (e.g. non-safety vs safety bus, combination of both);
- determining the detection values that would reliably detect unbalanced electrical voltage (e.g. undervoltage, negative phase sequence) under all plant conditions;
- using manual action (based on alarms) vs automatic disconnection (e.g. reliability of manual action, margin for operational time) to provide timely and reliable responses;
- using OPC protection in large inductive motors;
- using "analogue" relays vs "smart" protection relays, though qualification of "smart" relays (SW qualification) when installed on the safety bus has needed to be carefully considered;
- coping with spurious actuation of unbalanced electrical voltage detection/actuation system.

Appendix II provides details on specific technical solutions that were designed, verified, tested and implemented at various plants to cope with unbalanced electrical voltage in electrical power systems important to safety.

4.3. Strengthening international co-operation to advance nuclear safety

The operating experience shows that unbalanced electrical voltage conditions can be difficult to detect, but when they do occur, they can cause damage or loss of functionality to electrical equipment, including safety equipment, in a short period of time.

The design and implementation of permanent solutions requires proper understanding of the behaviour of magnitude and angle of phase to phase, phase to earth, positive, negative, and zero sequence voltage and current caused during the OPC event, as well as all the plant operating conditions. The following design principles need to be considered:

- reliability of OPC detection;
- spurious actuation concerns;
- prevention of loss of all redundant safety features due to a failure of an OPC detection system.

The presentations and discussions at the workshop showed that the problems identified in SRS-91 (NEA, 2016a) with developing and implementing detection methods are those that have indeed been experienced. While additional technical problems have been experienced with implementations, which suggest an update to SRS-91 might be considered, and the original publication remains relevant today, problems continue to be experienced with qualifying commercial "smart" protection relays for which better industry guidance would be considered beneficial. For example, these smart devices can be implemented as separate or standalone field components or embedded as components in other equipment or systems and can be used to increase plant reliability, enhance safe operation, improve testing and monitor functions. However, the use of smart devices may potentially introduce new hazards, vulnerabilities and failure modes.

IAEA Nuclear Energy Series No. NR-T-3.31, "Challenges and Approaches for Selecting, Assessing and Qualifying Commercial Industrial Digital Instrumentation and Control Equipment for Use in Nuclear Power Plant Applications" (IAEA, 2020), provides additional information regarding the justification and qualification processes for digital commercial products with limited functionality (equivalent to smart devices in this document).

An IAEA Safety Report (in preparation) discusses the safety aspects and design criteria associated with the safe use of industrial commercial smart devices in systems important to safety including: functional suitability and the evidence required to demonstrate this suitability, quality, qualification, consideration of certification by non-nuclear organisations using non-nuclear standards, and aspects affecting integration of the smart device into existing electrical, I&C and other systems in order to ensure that the smart device will retain its suitability for the required lifetime.

Another source for qualification of a smart device for the safe use in the plant systems important to safety is IEC 62671 (IEC, 2013). This standard has been specifically developed for selecting and using digital devices of limited functionality (i.e. smart devices) that can be applied for previously developed devices. It addresses certain devices that are candidates for use in nuclear power plants, but which contain embedded software or electronically-configured digital circuits that have not been produced to other nuclear IEC standards which one seeks to apply to systems and equipment important to safety in nuclear power plants. At present, IEC 62671 concentrates on the individual cases of a smart device (or a family of such devices) in a nuclear plant and includes only a limited consideration of the possibility of more than one smart device and the consequent possibility of common cause failures.

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Appendix I

Workshop Agenda

Day 1: Tuesday, 27 October 2020 (Virtual Meeting)		
Time	***Topic***	***Presenter***
	OPENING	
11:00	Welcome and opening remarks	Mr Greg Rzentkowski (Director, IAEA NSNI)
11:05	Welcome and opening remarks	Mr Andrew White (Deputy HoD, NEA NSTR)
11:10	Objectives of the Workshop	Mr Alexander Duchac (IAEA)
11:15	Instructions on the virtual meeting implementation (GSAN page)	Mr Ruslan Minibaev (IAEA)
	TOPICAL PRESENTATIONS (Industry activities)	
11:20	WGELEC overview	Mr Pepper, WGELEC Chair (United Kingdom)
11:30	Co-ordination of unbalance protection: Summation of all information into a coordinated protection scheme.	Mr Magnus Knutson (Sweden)
12:00	Behaviour of the Spanish nuclear power plants in relation to the OPC	Mr Carlos Martinez Sánchez (Spain)
12:30	Coping status for the OPC in Korea	Mr In Jun Hwang (Korea)
13:00	Analysis and corrective actions implementation for OPC and unbalanced voltage in the high voltage external network of the Belgian nuclear power plants	Mr Raphael Renard (Belgium)
13:30	Discussion	All
14:00	*End of day 1*	
Day 2: Wednesday, 28 October 2020 (Virtual Meeting)		
Time	***Topic***	***Presenter***
	TOPICAL PRESENTATIONS (Industry activities)	
11:00	Forsmark 1-3 – Measures to manage open phase conditions	Mr Albert Nilsson (Sweden)
11:30	Implementation of Measures to open phase in Doel Nuclear Power Plant	Mr Dirk De Win (Belgium)
12:00	Open phase analysis at Cernavoda Nuclear Power Plant and measures to mitigate its effects	Mr Liviu Matescu (Romania)
12:30	Development of Grid Open Phase Detection & Safety Case Strategy in the United Kingdom	Mr John Reilly (United Kingdom)
13:00	Measures to detect open phase conditions in German nuclear power plants	Mr Robert Arians (Germany)
13:30	Open Phase Condition Update Bruce A Unit 1	Mr Jeff Stevenson (Canada)
14:00	Discussion	All
14:30	*End of day 2*	
Day 3: Thursday, 29 October 2020 (Virtual Meeting)		
Time	***Topic***	***Presenter***
	TOPICAL PRESENTATIONS (Regulatory position/activities)	
11:00	Regulatory action for OPC potential at nuclear facilities in Japan	Mr Kazuyoshi Kataoka (Japan)
11:30	ONR expectations on measures to manage OPC at existing facilities and new reactors	Mr Kevin Pepper (United Kingdom)
12:00	Regulatory perspectives on the management of "Degraded Power Supplies" in nuclear power plants	Mr Mattias Karlsson (Sweden)
12:30	Regulatory approach on measures to manage open phase conditions	Mr Constantin Alex Sumanariu (Romania)
13:00	Current implementation status of measures to manage open phase conditions in electrical power systems of nuclear power plants	Mr Roy Mathew (United States)
13:30	Open phase condition consideration	Mr Marcel van Berlo
14:00	Discussion / closing remarks	All/WGELEC/IAEA
14:30	*End of virtual meeting*	

Appendix II

This appendix is made available upon request by the NEA by emailing the contact person indicated on the website of WGELEC: www.oecd-nea.org/jcms/pl_25383.