Journal of ELECTRICAL ENGINEERING, VOL. 62, NO. 3, 2011, 173–180

REVIEWS - LETTERS - REPORTS

DISTURBANCES IN THE EUROPEAN NUCLEAR POWER PLANT SAFETY RELATED ELECTRICAL SYSTEMS

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This work is part of the European Clearinghouse on Nuclear Power Plant Operational Experience Feedback (NPP-OEF) activity carried out at the Joint Research Centre/Institute for Energy (JRC/IE) with the participation of ten EU Regulatory Authorities. It investigates the Forsmark-1 event of July 2006, as well as about 120 disturbances in the plant electrical systems that were reported to the Incident Reporting System (IRS) and US Licensee Event Reports (LER) in the period 1985-2008. The aim of the work was to provide important insights from the Forsmark event of July 2006 and illustrate some vulnerabilities of the plant electrical system to over voltage transients. It identified electrical equipment involved, failure modes, contributing factors, actual and potential consequences, and corrective actions. Initiating factors and associated root causes were also analysed. The analysis of International Operation Experience Feedback revealed number of events that involved disturbances in the plant electrical systems, and which may have features in common with the Forsmark-1 event. It underlines the importance of sharing lessons learned from design modifications made at another unit of similar design that if known, it could have identified susceptibility of emergency diesel generators to common mode failure before the event occurred. This paper also summarizes international projects that were initiated by Forsmark event, as well as important lessons that still can be learned from Forsmark event. This paper presents actions taken at nuclear power plants and regulatory authorities in different countries to prevent similar event to occur.

Keywords: Forsmark event, nuclear power plant, disturbances in the plant electrical systems

1 INTRODUCTION

Nuclear Power Plant (NPP) operational experience has been used for many years to improve the safety of nuclear facilities throughout the world.

In the European Union, in order to support the Community activities on evaluation of NPP operational events, a centralized regional “Clearinghouse on NPP operational experience feedback (OEF) was established in 2008 at the JRC-IE, on request of nuclear Safety Authorities of several European Member States, in order to improve the communication and information sharing on OEF, to promote regional collaboration on analyses of operational experience and dissemination of the lessons learned [1].

Ten EU Regulatory Authorities are currently participating to the EU Clearinghouse on OEF for NPPs: Finland, Hungary, Lithuania, the Netherlands, Romania, Slovenia, Switzerland, Czech Republic, France and Spain (the last 3 being observers). Furthermore, a close cooperation with the European Technical Support Organizations has started, in particular IRSN and GRS.

One of the technical tasks of the European Clearinghouse consists in performing in depth analysis of families of events (“topical studies) in order to identify the main recurring causes, contributing factors, lessons learned and to disseminate and promote recommendations aiming at reducing the reoccurrence of similar events in the future [2–3].

The operational event at the Forsmark-1 of 25 July 2006 was selected as representative of electrical incidents and, in collaboration with the IAEA, the disturbances in the plant electrical systems have been analysed [4].

The Incident Reporting System (IRS), jointly operated by the IAEA and the Nuclear Energy Agency of the OECD (OECD-NEA), was chosen as a reference database to identify relevant events that occurred in the electrical grid or in plant electrical systems.

US Licensee Event Reports [5] (LER) were complementary to the IRS database, another important source of information about events that involved disturbances in the plant electrical systems.

2 WHAT HAPPENED AT FORSMARK IN JULY 2006

The Forsmark Unit 1 is a Boiling Water Reactor (BWR) type reactor with a nominal electrical power of 990 MW, with two turbines. It has four trains of emergency power supply, each equipped with an Uninterruptible Power Supply (UPS), battery, charger and emergency diesel generator (EDG). Each train has 50 % capacity in terms of coping with a design basis accident, and a gas turbine that is regarded as the power source of last resort

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DOI: 10.2478/v10187-011-0029-8, ISSN 1335-3632

in case all auxiliary and emergency power supplies are unavailable.

On 26 July 2006, the Forsmark-1 was operating at rated power while the asymmetric short circuit occurred in the 400 kV substation due to an error of maintenance personnel [6]. This resulted in a substantial drop in voltage in two output phases; this fault then further propagated towards the plant electrical systems. The electrical protection commanded to open the 400 kV circuit breakers; this took however a much longer time than originally designed; the generator was already overexcited, and thus the output voltage instantly rose to 118 % of the nominal value. Because both generator breakers remained connected to the plant electrical systems, the over-voltage propagated through the unit household transformers to the plant's 6 kV electrical buses, as well as the 500 V safety buses. If the electrical protection had isolated the short circuit in the 400 kV substation in a shorter time (as should have been the case with this design), the generator voltage output would have remained within tolerable limits.

The voltage transient caused a significant safety effect to the plant safety related electrical systems. As a consequence, number of other failures occurred that resulted in loosing 2 out of 4 UPS system. Only two EDG succeeded to connect their electrical output to associated safety buses because of the latent common cause failure (CCF) in the design of EDG speed control protection, which was powered by the UPS bus that belongs to the same redundancy as EDG. It is not known why this CCF has not disabled the other two EDG. Potential threat to the plant safety was obvious.

The event clearly demonstrated how a single human error led to a chain of events that revealed a number of shortcomings in the 'defence in depth at the plant electrical systems. Although the plant personnel, acting professionally in line with the plant emergency operating procedures, were able to restore the electrical power supply in about 22 minutes, the core coolant inventory was nevertheless partially degraded.

3 WHAT CAN BE LEARNED FROM THE FORSMARK–1 EVENT?

The Forsmark-1 event and its outcome raised a number of issues relating to robustness of the plant electrical power supply to withstand disturbances in the grid and also relating to the plant electrical systems. According to the manual, the electrical design of the plant is supposed to ensure appropriate selectivity of the electrical protection, so that a potentially dangerous disturbance in the external grid system, as well as any internal failures of plant electrical components (transformers, motors, *etc*), are isolated in time without propagating to the entire plant electrical system. An appropriate defence-in-depth strategy should therefore be considered in the design so as to allow for different contingencies to ensure that the normal or auxiliary power supply is restored and at least that the emergency power supply is always available.

3.1 Design safety consideration

The Forsmark-1 event revealed a major vulnerability of the emergency power supply affecting both the UPS system and EDG, which could potentially lead to a station blackout. Since the commissioning of Forsmark-1, its plant electrical systems have been gradually upgraded. Neither safety analysis associated with modifications on systems important to safety, nor a periodic safety review involving a review of the plant design basis was effective in detecting latent common-mode design problems.

It is an interesting fact that the Olkiluoto plant in Finland had an EDG speed control system dependency on UPS back-up that was similar to the Forsmark-1 configuration. However, another plant of very similar design had modified the power supply of the EDG speed control system and removed the dependency on UPS. This information was probably not known to Forsmark personnel.

Long time ago, the aviation industry introduced a good practice to inform airline operators on any airplane defects that may have potentially safety consequence on operation of the aircraft. Similarly to aviation industry, perhaps the nuclear power plant architect designer should also inform other power plants of the design concerned about the identified latent deficiency and proposal for solution to fix it.

3.2 Electrical protection considerations

The plant electrical protection system should be so designed as to be able to clear potential electrical faults in good time in order to prevent the electrical fault being propagated deep into the plant's electrical systems, including safety buses. This protection must ensure appropriate circuit breaker coordination so as to prevent overloading of the plant's electrical systems.

Both of the Forsmark-1 generators are equipped with underfrequency protection. However, the underfrequency protection operated incorrectly because of incorrectly connected wiring. It was subsequently found that testing of the new protection had failed to reveal the incorrect phase setting. If the underfrequency protection had operated as designed, this would have helped in transferring the house load buses to the auxiliary power supply without delay. In both cases, the electrical buses would have been automatically transferred to the auxiliary power supply without requiring the EDG to start.

Comprehensive post-modification testing is very important, especially when the old electromechanical components are replaced by modern ones. It was also observed in the past that nuclear power plants took several months to test electrical systems and equipment during initial commissioning. Today, testing of electrical systems after

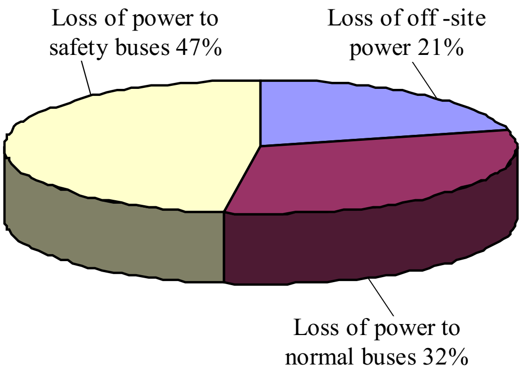

Fig. 1. Major failure mode distribution in (%)

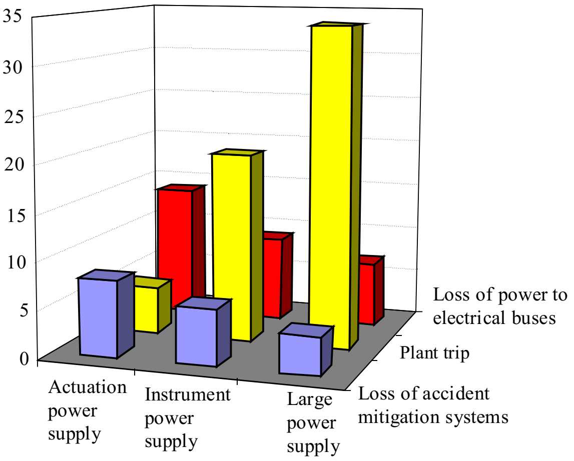

Fig. 2. Dominant failure modes on loss of power supply

modifications is often performed in a matter of hours. Sufficient time must be allocated for thorough testing of electrical systems after modifications. Furthermore, adequate test coverage needs to be designed and implemented.

3.3 The International Task Group on defence in depth in the plant electrical system

In response to the Forsmark-1 event of July 2006, OECD/NEA launched (in 2008) a CSNI (Committee on the Safety of Nuclear Installations) Task Group on Defence in Depth in Electrical Systems and Grid interactions (DIDELSYS). The objective of the CSNI Task Group was to draw up a document which sets out minimum requirements for addressing the robustness of safety related electrical systems. DIDELSYS final report [7] was published in November 2009 and provides state-of-the-art information in this area, taking into account the use of new technologies and the problems encountered when existing plants are modernised, interaction with the grid and ways of improving the communication and coordination between the grid (operator and regulator), the nuclear safety authorities and the Licensees. The Task Group revealed major findings that can be summarized as follows; (i) Range of voltage transients could be wider than originally considered in plant design; (ii) Voltage degradations and its impact on electrical equipment should is not always understood; (iii) Existing defence in depth concept for plant electrical systems to withstand external & internal electrical impact may not be sufficient; and (iv) Testing and Simulation codes for plant electrical systems are rarely used. The report also pointed out that the power plant design should provide for diverse means for promptly supplying power to cooling systems other than electrically driven (steam, gas). It also had a brief to set minimum requirements for improving those relations. The EU Clearinghouse contributed to the Task Group activity, particularly in the area of analysing and summarising the relevant international operation experience feedback.

4 FEEDBACK FROM INTERNATIONAL OPERATING EXPERIENCE

4.1 Incident reporting System

The IAEA/OECD/NEA Incident Reporting System (IRS) was chosen as a reference database to identify relevant events that occurred in the electrical grid or in plant electrical systems.

When screening the IRS database, some 120 events were identified which have a common denominator — disturbances in the plant electrical systems and/or problems with electrical power supply, including grid disturbances. It appears that the disturbances in plant electrical systems are quite common events. The IRS database contains events that were voluntarily reported by participating countries; *ie* the only events reported are those which the power plant operators or regulatory bodies consider to be important to safety. Although reporting of low level events, as well as near misses, is continuously improving, a large number of events still remain either undetected or unreported.

The United States Licensee Event Reports (LER) were complementary to the IRS database, as another important source of information about events that involved disturbances in the plant electrical systems. About 19 relevant reports from the plants to the US NRC were also included, in order to better illustrate the different types of events that involved the grid or plant electrical systems.

For the purposes of this paper, some events involving disturbances in the grid and/or plant electrical systems were identified that may be used for further considerations on operational experience feedback. The time period chosen for this screening includes events reported between 1984 and June 2008.

4.2 Results of IRS database screening

The IRS database screening showed that disturbances in the grid or plant electrical systems are quite common. These events occurred at nuclear power plants worldwide.

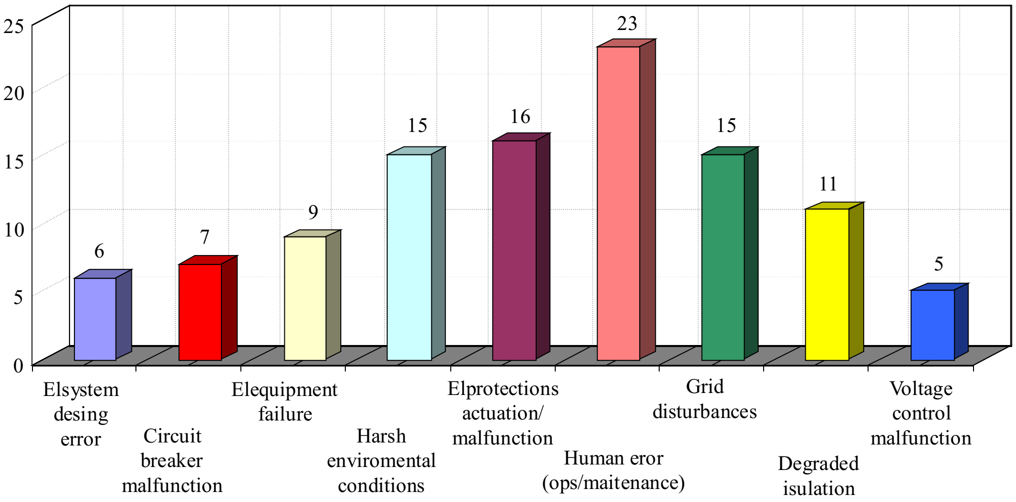

Fig. 3. Contributing factors identified in the selected events

Disturbances reported in the plant electrical systems concerned the following major failure modes (see Fig. 1): Loss of off-site power (21 %), Loss of power to normal electrical buses (32 %); and Loss of power to safety buses (47 %). Although the 24-year time interval during which all of these events were reported is considered as relatively long, the number of events that involved failures of electrical supply — in particular to the plant safety buses — appears nevertheless to be quite high. Even the number of reported events that caused Loss of off-site power at the plant seems to be significant.

It is important to mention that the plant safety buses provide electrical supply to the systems that are important for safety. De-energizing the safety buses for a lengthy period or during accidental conditions without any possibility of recovering power either from the standard power supply or EDG might lead to a deterioration of several safety functions at the plant. Fortunately, none of the events reported in the IRS database occurred simultaneously with another initiating event (*eg* loss of coolant) that might require the operation of plant systems important to safety.

Another category that requires attention is the dominant failure mode for loss of specific power supply. Figure 2 shows the distribution of dominant failure modes for loss of instrument channel supply, large power supply, and actuation power supply. In terms of analytical needs, the loss of instrument channel represents a failure or spurious actuation of any measurement (I&C) component; the loss of large power supply represents an internal or external event that has led to the loss of main power lines, malfunction of major electrical equipment (generator, transformer, switchyard, *etc*) or human error (operational or maintenance); the actuation power supply represents failures of electrical components (circuit breakers, transformers, *etc*).

Figure 3 shows the number of dominant failure modes for loss of specific power supply. The results in this chart are more or less as expected: the loss of large power supplies led in most cases to the plant trip, while the loss of actuation and instrument power supply led in particular to loss of power to electrical buses and, consequently, to failure of accident mitigation systems.

As a result, the loss of actuation and instrument power supply in general has more significant consequences than just the loss of large power supply.

What actually caused all these failures? A closer look at the event analyses shows a number of failure modes that involved different types of electrical equipment and which had an effect on the proper functioning of actuation power supply, instrument channel supply, and large power supply. The following sections will discuss failure modes and the factors that contribute to them. In addition, some examples of each contributor category are presented to illustrate circumstances and their role in the sequence of events.

4.3 Factors contributing to the selected events

Closer evaluation of IRS events related to disturbances in plant electrical systems helped reveal a number of common contributing factors (in some cases initiators) for a given group of reported events. It should be understood that the list of events reported in the IRS database may not be complete, since not all loss of offsite power events are reported. Reporting to the IRS system is voluntary, and therefore the information obtained should be treated with care. Not all overvoltage events are explicitly identified. Therefore, this report presents information on the results of IRS screening and US NPP Licensee Event Reports without drawing any general conclusions, to show that there is international operating experience in addition to the Forsmark-1 event. In this survey, and for certain groups of events, a number of representative contributing factors have been identified. Figure 3 shows the distribution of these contributing factors by category.

4.3.1 Human error

As can be seen, human error is the biggest contributor to the initiators of the reported events. Human error includes errors of both plant and contractor personnel (misalignment of electrical systems, tasks performed in a sequence different from that which is required, omission of an operation/incorrect operation performed in a sequence, switching error, maintenance error, *etc*).

Human errors may have adverse and sometimes unpredictable consequences. The Forsmark-1 event was in fact triggered by an external contractors error while carrying out maintenance activities in the switchyard. It is very important to carefully analyse every event that involves human error and to take appropriate corrective measures.

4.3.2 Electrical protections

Failures of electrical protections make up another significant category of contributing factors. The corresponding failure modes involve incorrect setpoints, failures to actuate due to malfunction or ageing of internal components (mostly relay elements), as well as spurious actuation. This is probably not surprising, as a large number of electrical protections are installed at the plant, and there are demanding design requirements for electrical protections. The electrical protections are designed to actuate precisely when they ought to (the time is measured in milliseconds). The reason for this is that the plant has to remain connected in case there are some smaller disturbances in the grid. However, the electrical protection should not actuate too early, as this may cause unnecessary power reduction or plant trip and loss of production. On the other hand, the electrical protections should actuate early enough to isolate the voltage/current disturbance or faulted equipment so as to avoid of the electrical fault being propagated to the plant electrical systems.

Another design feature of electrical protections is that a voting logic (*eg* 2 out of 3), which is common in the design of reactor protection systems, is not applied in this case. Electrical protections are designed as single protecting units, which actuate in milliseconds; this sometimes involves simultaneous measurement of different parameters, such as voltage and current in the different parts of the plant electrical system. The configuration and setpoints of electrical protections should ensure appropriate selectivity in order to avoid unnecessary propagation of electrical disturbance to the electrical systems of the entire plant.

To avoid single failure of a safety bus or an EDG due to spurious/actual activation of electrical protection there are specific design requirements at the various plants. US plants have no electrical protections on safety buses, only on feeders. In the event of a short circuit, the corresponding circuit breakers are designed to open without damage (or risk of fire). Some European plants, on the other hand, have electrical protections at safety buses. There have been cases of spurious actuation of electrical protections which have prevented the powering of the safety bus. It is a matter of the design approach to electrical protections at the plant. Nevertheless, it is important that appropriate defence in depth in the plant electrical systems is taken into consideration during the design of new power plants, as well as during the scheduled periodic safety reviews of older plants.

The US Nuclear Regulatory Commission (NRC) issued an information notice to notify addressees of a loss-of-offsite-power and dual-unit trip event that occurred at one plant due to circuit transformer failures and incorrect switchyard bus differential relay settings. The NRC expects addressees to review the information in terms of its applicability to their facilities and to consider actions, as appropriate, for avoiding similar problems. However, the suggestions contained in this information notice are not formal NRC requirements; therefore, no specific action or written response is required [8].

4.3.3 Grid disturbances

Very few events were reported in the IRS database in relation to grid disturbances. One possible explanation is that a grid disturbance — unless it has an impact on plant operation — is not always reported. A grid operator has no obligation to report to the IRS. Therefore, many grid disturbances that did not develop into events triggering the plant's electrical systems (main power lines, auxiliary and back up power supplies) go unreported.

About 12 events were reported in relation to electrical grid disturbances in Licensee Event Reports from US nuclear power plants (which were not reported to the IRS). These reports are very relevant, which is why they are included in this report. They provide valuable insights into how the plant electrical system, as well as the plant itself, responded to the electrical grid disturbances.

The design of grid systems is country specific, as are the configuration of the plant output and the external power supply. This may vary significantly from country to country and between plant sites. The interaction between the grid system and the plant may therefore be very specific. The grid disturbances may have an impact on several local substations, causing partial disruption or simultaneous loss of main output as well as auxiliary (start-up) power lines. Such disturbances can lead to common mode failures and should be given careful consideration when designing the plant power supply system.

The industry has to re-evaluate its understanding of the design of NPP electrical systems and their interactions with the external grid. Lost knowledge from the design stage tends to be replaced by the application of standards. However, standards have their limits when it comes to completeness and guidance. Full understanding of the design of NPP electrical systems has been recognized to be of prime importance for formulating correct and comprehensive specifications for new equipment.

4.3.4 Harsh environmental conditions

Harsh environmental conditions, such as high winds and snow, freezing rain, lightning, earthquake, and flooding, have been reported to the IRS system. This category, along with grid disturbances, is the third largest category after human error, and the safety significance of some of these events is obvious. In most cases, harsh environmental conditions affected the plant's main and auxiliary power supplies, and led in some cases to a forced house load operation or a long-term mission on the part of the EDGs to maintain electrical power supplies. A combination of freezing rain, low temperatures and strong winds may cause a short circuit on the open air power transmission switchyard that serves the entire nuclear power plant. Following loss of off-site power, a manual reconfiguration of essential electrical supplies was needed to restore supply to the house load and safety buses from a standard power supply scheme and relive the diesel generators from duty.

4.3.5 Electrical equipment failures

This category involves failures of yet other items of electrical equipment, such as transformers (internal winding short circuit, high voltage penetration short circuits), fuses, inverters, motor short circuits, etc. It was observed that, while failures of minor electrical equipment (motors, fuses, small transformers) could be easily isolated without having an impact on the plant electrical systems, problems with main or house load transformers can cause serious disturbances in the plant's electrical systems. In addition, a fire risk is always present owing to the inflammable oil contained in transformer vessels.

4.3.6 Degraded insulation

Eleven events were reported that involved problems in the plant electrical systems due to degraded insulation of electrical conductors, cables and penetrations. One plant reported that, during normal operation at its rated power, a short circuit incident occurred in one of the medium voltage AC buses, and resulted in a decrease of bus voltage, and reduced coolant flow in one of the reactor coolant loops, causing the reactor to automatically trip. Inspection showed a burnout on the u-v phase conductors near the connecting portion to the tie breaker due to a short circuit of the conductors.

One IRS report addressed potential problems that are common to several nuclear power plants caused by the failure of electrical bus bars due to cracked insulation and moisture or debris build-up in the bus bar housing. Insulation failure, along with moisture or debris, led to undesired phase-to-phase or phase-to-ground faults, which resulted in catastrophic failures of buses. Another plant reported that degraded insulation resistance of the current transformer on phase A output caused a short circuit and subsequent disconnect of the main and house load transformer.

Events like those described above demonstrate that, among electrical and I&C equipment, it is electrical cables and connectors that are the most limiting factors in terms of the long term operation of the power plant. In many older units, electrical cables for equipment and motors — including the safety related equipment and motors — were insulated with PVC, by installers that were not qualified, and had no real knowledge of environmental conditions, or the ability to determine the projected lifetime. There is therefore a risk that an unqualified cable may not operate correctly under accident conditions. Currently, it is estimated that the direct cost of unit recabling could be equivalent to 2.5 % of the NPP unit price and that such an operation would take up to 1.5 years [9]. Therefore, special attention is being paid to the replacement of PVC or other unqualified cables with new qualified ones, or at least to running re-qualification programmes which include prediction of ageing. Some power plants have already implemented a specimen surveillance programme for electrical cables. Under this programme a cable specimen is stored in the containment to simulate accumulated thermal and radiation aging. Tests are then performed on the samples as described in the relevant technical reference documents.

4.3.7 Circuit breaker malfunctions

Considering the large number of electrical circuit breakers in every plant, the number of reported events involving failures of electrical circuit breakers or their actuation system is actually not so significant. An electrical circuit breaker is an active component that has a limited design life. Many plants have already replaced old, obsolete breakers (especially oil circuit breakers) with new ones (in most cases SF6) that are highly reliable and are capable of opening during a short circuit.

Nevertheless, circuit breaker failures — especially in high voltage systems — can cause serious disruption in the plant electrical system. For example, one plant reported a serious grid power disturbance due to a 220 kV circuit breaker failing to reconnect the nearby coal fired plant, which caused voltage and frequency fluctuations ranging from 45 to 53 Hz in the plant's electrical system. The voltage of the units auxiliary power buses dropped from 6 kV to 3 kV. The 110/220 kV outdoors switchgear tripped and power was lost in all 6 kV unit auxiliary power buses. All diesel generators connected to the relevant 6 kV buses.

4.3.8 Voltage control malfunctions

A special category of electrical system failures relates to voltage control system malfunctions. This involves both the main and the emergency diesel generator voltage control systems. One plant reported EDG problems in maintaining the required voltage after startup, due to malfunction of the excitation system.

One IRS report discusses how a malfunction in the main generator voltage regulator might increase generator output voltage, which could cause an overvoltage condition at the vital buses powering the electrical equipment that is important for safety. The over excitation was caused by a malfunction in the voltage regulator circuitry.

In most cases the plant electrical protection system worked properly and was able to isolate the overvoltage by opening the generator or main output breaker without propagating overvoltage conditions to the electrical system of the entire plant.

However, a recent event shows how significant the disturbances to the plant electrical system that might be caused by a malfunctioning generator voltage control system can be. The malfunction of the generator excitation system led to an overvoltage condition, putting the recirculation pump inertia mechanism, which was designed on electromechanical principles, out of service. This inertia mechanism was implemented as part of the power up-rating and ensured necessary cast-down time for core cooling during the reactor trip. Instead, the recirculation pumps stopped in one second, which resulted in temporarily inadequate core cooling. The generator excitation system was modified before the start-up of the plant. This event demonstrates the importance of adequate assessment and testing when modifications are made to non-safety related electrical systems which, if they were to malfunction, might lead to the failure of an electrical system that is vital to safety.

4.3.9 Electrical system design error

Design errors in plant electrical systems were also identified as being among the contributing factors in selected events. Design errors are mostly hidden and only come to light after the failure has occurred. Plant safety reassessment using probabilistic methods may help to reveal some hidden design errors. Failure mode and effect analysis is a very effective tool in analyzing the specific system design in detail, but it is a complex analysis which is not needed for every plant system.

Other possible design errors may be imported into the plant design during the modification process. It was recognized that small gradual changes of the original design, when added together over time, could invalidate the original design assumptions and safety analysis.

Several examples can be found in the IRS database of design errors that have caused problems in the plant electrical systems, although, in general, such identified design errors were relatively few in number. For illustration, at one plant, a potential safety-related problem was identified which could have resulted in the loss of a vital electrical bus due to overloads caused by connecting excessive loads to the bus during a loss-of-coolant accident. Such overloading would actuate the bus overload protective device and the associated lock-out device, to prevent the bus being energized from any other source, including the emergency diesel generator. Similar overloading of multiple buses during an accident could disable redundant trains of safety-related equipment. A failure modes and effects analysis (FMEA) could be a powerful tool to identify latent vulnerabilities in the design of the plant electrical systems important to safety. For example, at one plant the FMEA possible scenarios of emergency diesel generator EDGs overloading, potentially resulting in the loss of both EDGs of a unit due to such overloading.

5 CONCLUDING REMARKS

The Forsmark-1 event can be regarded as a very complex event with a number of weaknesses which were related to deficiencies in all three categories: equipment, personnel and procedures. In particular because of its implications for the plant safety, this event attracted a great deal of attention, especially among BWR operators, and it is also of generic importance to other plant operators.

The overview of International Operation Experience Feedback, which is part of this report, describes some of the events reported to IRS by nuclear power plants worldwide relating to disturbances in plant electrical systems. In addition, this feedback review provides insights into failure modes, and contributing factors, as well as features which are shared with the Forsmark-1 event on disturbances in plant electrical systems. Some statistical data on events related to plant electrical systems illustrate the frequency and distribution of factors that contribute to events involving disturbances in the plant electrical systems. However, these data should be regarded as having only illustrative value, because the IRS database may be incomplete; in particular, events occurring in the grid system, and involving grid disturbances that have no significant impact on plant power output, are not always reported.

As shown above, events involving disturbances in the grid or plant electrical systems are fairly common. Quite large numbers of reported events involved safety buses; a number of events that involved the LOOP sequence are also significant. Grid disturbances as a result of harsh environmental conditions (severe weather, lightning strike) are also quite common. Voltage transients caused by lightning may have serious consequences for the plant electrical systems; a range of voltage surge transients including anticipated lightning surges may therefore require a review of the current design basis.

The Forsmark-1 event, and especially its outcome, raised a number of issues relating to plant electrical systems which are important to safety. Many of the issues that were highlighted during the investigation of the causes of the Forsmark-1 event are generic in nature.

The various countries should learn from each other on the basis of the outcomes of the investigations in the Forsmark-1 event. Some of the proposed corrective measures in Sweden may be directly applicable to other countries too.

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Received 22 April 2010

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