The (Un) interruptible Power Supply

Loss of 400 kV supply and subsequent failure to start emergency diesel-generators in trains A and B at the Forsmark 1 unit on 25 July 2006

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My summer holidays in the archipelago were soon coming to an end. On 24 July I had been in contact with my deputy Lennart Carlsson, who was on duty as acting director, about the past week's development at SKI. Lennart confirmed that everything was calm and quiet, and I judged that I would be able to come back to a clean desk at the office and with the chance to tackle some of the long term issues. This was the day before the Forsmark incident...

The incident was initiated by a short-circuit in the main switchyard. The voltage and frequency fluctuations that then ensued, together with additional components failures, resulted in the loss, for about 22 minutes, of two of the four redundant subdivisions in several safety systems. After 35 minutes the operators had been able to reset the safety sequences that had been activated and to place the unit in a normal shutdown condition.

There were to follow weeks of intensive activity at SKI, and with visits and talks with Forsmark, contacts with the media and the Government, and of answering questions from the representatives of the electricity market. An extensive effort was carried out, to gain an understanding of the events, to evaluate how Forsmark had reacted, and to prepare for the decisions that would be needed to take.

Following modifications in the design of the emergency power systems, SKI has now granted Forsmark units 1 and 2 the permission to resume operations again. This permission is accompanied by requirements and conditions related to the procedures for testing and control, and to the way management reacts on the discovery of weaknesses in the in-depth defences.

The event is regarded as severe due to the failure of part of the emergency power systems to operate when called upon. It was obvious that the unit had not reacted to the disturbance in the way anticipated in the relevant Safety Analysis Report. However, the reactor was shutdown, and core cooling and residual heat removal were ensured during the entire event by the automatic functions activated. No release of radioactivity ensued, allowing the event to be classified as level 2 on the international INES scale.

The Forsmark 1 unit

Forsmark 1, which started commercial operations in 1980, is a Boiling Water Reactor with a net output of 1016 MW_e and with two turbines. The safety systems are designed with four-fold redundancy. The four trains (A, B, C and D) are physically separated and encompass electronic, electrical and mechanical equipments.

During maintenance work in the 400 kV switchyard a short-circuit occurred on a 400 kV bus-bar, that was not isolated by the common bus-bar safeguard. This bus-bar lost voltage rapidly and Forsmark 1 was disconnected from the grid by activation of the under-voltage protection that opened both unit breakers. This caused load shedding in both turbo-generator units, and a voltage peak of 120% of nominal value was generated for about one (1) second. Reactor power was reduced automatically to 25% of nominal by a partial scram and run-back of the recirculation pumps.

Voltage transient

The transient over-voltage propagated down through the transformers of the electrical systems of the unit and tripped the rectifiers and inverters on the battery-supported 220 V AC grid of the uninterruptible power supply (UPS) trains A and B. This voltage transient did not, however, affect trains C and D.

The unit went into house-load operation, i.e. power production just sufficient to meet the internal needs of the plant, prior to signals being received for reactor scram, isolation of the primary containment and activation of the reactor safety systems. Signals were also received for tripping the two turbo-generators. The turbo-generator breakers remained closed, however, and power continued to be supplied to the electrical systems, although at a slowly decreasing voltage and frequency, as the generators ran down.

Diesel generators disconnected

Due to under-frequency on the bus-bars supported by the emergency diesel generators (EDG), these were disconnected from the ordinary 6 kV on-site grid. Within one minute of the start of the event all four EDGs had received their start-on-under-voltage signals. EDG A and EDG B started up, but did not connect to their respective bus-bars. Upon loss of power on these bus-bars - in trains A and B - the automatic functions of the safety related equipment fed by these bus-bars failed and the associated monitoring in the control room was lost. A further consequence of the loss of power in trains A and B was the generation of several reactor scram signals activating a number of safety sequences.

Cooling water was fed

In this situation the shutdown reactor was being cooled by steam release from the reactor pressure vessel (RPV) via two water/steam valves in trains C and D, and one regulating valve in train B. Cooling water was fed into the RPV via the auxiliary feed-water pumps in trains C and D. Due to the inflow of cold water, and the steam outflow, the pressure in the RPV fell rapidly, from an initial 7 MPa, and stabilized at a lower value. The water level in the RPV also fell rapidly at first, but stabilized after some 20 minutes when steam outflow and coolant inflow became equalized. At its lowest level, the water level in the RPV was 1.9 m above the reactor core. At that time the pressure in the RPV was 1.5 MPa, and falling due to the cooling process. The low-pressure reactor core cooling system in trains C and D would have been activated had the pressure fallen to below 1.2 MPa

Re-established all power supplies

After 22 minutes the bus-bars fed by the EDGs in trains A and B were reconnected by the operators to the ordinary 6kV grid, which had remained operational during the entire event through connection to the 70 kV off-site grid. These manual actions re-established all power supplies to the unit, and the operators could confirm that all control rods were inserted into the reactor core. From this point on, all sections of the auxiliary feed-water system and the low-pressure emergency core cooling system were active. The RPV water level increased rapidly, and the water inflow was stopped manually when the level had reached 5.3 m above the core. The safety sequences that had been activated were reset, and the water/steam valves were closed. After a total of 45 minutes the operators could confirm that the unit was in a safe and stable condition.

Staff acted methodically

The control room staff had acted methodically, in accordance with their simulator training, work praxis and emergency operating routines, throughout the entire event sequence. The Licensee was quick to inform SKI of events following the reactor scram, and concluding that the causes underlying the event could be of a generic nature, was also quick to inform other licensees in Sweden and Finland of the matter. However, at that time the licensee did not altogether recognize the complexity of the event.

In its turn SKI informed the International Atomic Energy Agency (IAEA) of the event in a timely manner.

Consequences

The event resulted in no consequences for the general public, or the environment. The automatic response of the unit to the electrical upset was a reactor scram with a subsequent activation of the safety systems in two out of the four trains. Cooling of the shutdown reactor core was guaranteed during the entire event sequence.

Analysis of the process parameters recorded indicates that no 'maximum allowed limit' for the RPV was exceeded, and that fuel integrity was maintained at all times. Additionally it is concluded, with the exception of the components in the 400 kV switchyard, that there are no lasting damages in the electrical systems.

Significant weaknesses

Causes of the event and significant weaknesses shown up;

Failure in the 400 kV switchyard

During maintenance activities in the 400 kV switchyard, the need to enable an earth-fault protection was misjudged by Svenska Kraftnät (the state utility that runs the national electrical grid). As a result, a short-circuit that occurred during the course of the work was not isolated in due time by the common bus-bar safeguard. Had this happened the short-circuit could have been isolated within 100 ms, with a significantly milder electric disturbance as a result, and no consequences for the bus-bars fed by the EDGs.

Delayed opening of the generator breakers

The safeguard for under-frequency at the generator breakers did not function as expected during the event. Had this acted properly the EDG bus-bars would not have lost voltage, and the loss of power on these bus-bars in trains A and b would have been limited to two (2) seconds instead of 22 minutes.

This malfunction of the under-frequency safeguard devices for the turbine generator breakers was caused by a faulty coupling of phases in the power supply to these devices. An original faulty coupling was made in the middle of the 80's and remained unidentified. The new type of devices installed in 2005 being dependent on a correct phase coupling was unknown within the Licensee's organisation – an indication of weaknesses in the management of the modification process.

Unsuccessful start of the gas turbine

The electrical systems at Forsmark include a 70 kV gas turbine unit. A start-up signal was sent to this unit on the occurrence of the drop in voltage. Due to a faulty automation processor, however, the signal was not passed on to the start-up automation of the gas turbine itself. But since the 70 kV off-site grid was available throughout the event, the turbine was not actually needed.

Loss of rectifiers and inverters in the uninterruptible power supply (UPS)

The initial over-voltage resulted in the loss of the UPS in trains A and B within two (2) seconds. This was due to the activation of the DC voltage safeguard on over-voltage on both the rectifiers and the inverters in these UPS units. These activation limits were set according to the values recommended by the designers and accepted by the Licensee. The safeguard for the components functioned, although with inadequate selectivity. Had only the rectifiers been isolated and hence protecting the inverters, then the batteries would have been able to provide power to the bus-bars via the inverters, as expected. Thus component safeguard compromised the safety of the plant.

Tests made at the manufacturer's premises with the original safeguard settings show that the over-voltage protection for the UPS inverters functions as expected for voltages between 85% and 110% of nominal. The actual voltage transient at Forsmark 1 lay outside this band and the UPS units were disabled. The Licensee and the manufacturer have made exhaustive analyses to find the reasons for the UPS in trains C and D remaining operational. The conclusion drawn is that the AC voltage protection of the rectifiers in these units was activated by the under-voltage, and the inverters were then unaffected by the isolation of the rectifiers. Automatic restart of the UPS units took place when the voltage surge had decayed.

Unsuccessful connection of EDG in trains A and B

The emergency diesel generators in trains A and B started up, but did not tie into their 500 V bus-bars. This was because the EDG start-up automation includes a sensor for engine revolutions that is powered from the 220 V AC bus fed by the UPS. In trains A and B these sensors were without power and both EDGs tripped on a 'long-starting-time' signal.

Loss of information in the control room

A huge information flow into the control room was experienced during the event, and the complicated flow of signals was difficult to interpret. The loss of 220 V AC from the UPS in trains A and B resulted in the loss of important information needed to handle the event. Amongst other items lost were the indication of 'control rod in core' for the rods belonging to these trains, indications from the neutron monitoring system, and for coolant level and pressure in the reactor pressure vessel. The loss of these two UPS made the operators' workstations unavailable. Some of the mimic panels for the electrical systems indicated a faulty status for the trains still having power.

Relevance of the event for the other Swedish nuclear power plants

Three days after the event a letter was sent by SKI to all the Swedish licensees requesting information confirming that their nuclear power plants do not have the weaknesses shown up at Forsmark 1. The Licensee for the Oskarshamn nuclear power plant informed SKI on 2 August that units 1 and 2 had been shut down earlier that day. This was mainly due to the fact that the licensee could not show, in a sufficiently convincing manner, that these two units would not experience malfunctions similar to those at Forsmark 1.

Further issues

Several issues will need further analysis, and SKI welcomes international cooperation on some of the following ones:

- Root causes behind the fact that the UPS:s were not designed for such electrical transients as were experienced
- Selectivity between the ordinary grid and the battery/EDG fed grid so as to prevent disturbances from propagating down to the safety systems of the unit
- Arrangements for the feed-back of experience
- The plant modification process when new technology is applied to older plants
- The regulatory supervision and regulations
- Robustness of the emergency power supply system

I hope that by sharing our experiences of the incident at the Forsmark 1 unit, we will be able to raise the awareness of design deficiencies in emergency power systems that may be present in nuclear power plants outside Sweden.

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