Lessons learned from the Forsmark 1 event related to the safety-related electrical systems in the Belgian NPPs

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Abstract:
This paper describes the main steps of the assessment of the safety electrical system of the Belgian NPPs with regard to the lessons learned from the Forsmark 1 event of July, 25 2006.
This event and its lessons learned related to the electrical systems are shortly summarized. A short overview of a Belgian NPP electrical system is described, in particular the UPS equipment failing during such an event. The Belgian TSO (Bel V) has evaluated the event and formulated some requests to the licensee (Electrabel). An action plan has been determined by the licensee to verify and justify the design and the defence in depth of the safety electrical systems against an overvoltage transient. Bel V has examined and commented the studies and justifications delivered by the licensee; some relevant results of this assessment are also given. Finally, the licensee presented a set of short and long term corrective actions taking into account the Bel V assessment. Further expected developments are defined in the conclusions.

1 THE FORSMARK 1 EVENT – SUMMARY AND LESSONS LEARNED

1.1 Summary of the event (IAEA IRS 7788)

Forsmark 1 NPP was on July 25, 2006 in full power operation. During the maintenance activities in the offsite 400 kV switchyard a short circuit occurred after the opening of a disconnector. The default was not immediately eliminated by the protections due to improper connections. The voltage decreased very quickly and the unit breakers opened on undervoltage protections. This opening caused a loss of load on both turbine generator units and an overvoltage transient up to 120 % Un occurred during 1 s.
2 s later the rectifiers and inverters of two (out of the four) safety 220 Vac Uninterruptible Power Supplies (UPS) tripped on overvoltage and the two failed inverters were automatically by-passed.
The unit went shortly in house load operation; both turbine generators received a turbine trip signal but the generator breakers did not open on underfrequency signal. Therefore no automatic transfer occurred from the normal 400 kV network to the back-up 70 kV network. The frequency and voltage continued to decrease because of the reducing rotational speed of the generator rotor. When the undervoltage protection was activated in the two bus bars associated to the failed UPS, their supply was automatically switched to the by-pass transformer. The incoming breakers of the safety power 500 Vac bus bars opened on underfrequency signal. All offsite power sources were lost at this moment. Consequently the four Emergency Diesels Generators (EDGs) started on undervoltage. In the trains the EDGs

corresponding to the two failed UPS could not be connected to their 500 Vac bus bar because the 220 Vac voltage is necessary for the operation of the EDG.
From this stage two safety electrical trains remained out of voltage during more than 20 minutes. Afterwards the operators were able to reconnect manually the offsite power to the lost safety electrical trains.

1.2 Lessons learned

This section deals with the most significant lessons learned of this event wich are related to the safety electrical systems.

1. The set points of the overvoltage protections of the rectifier and the inverter must be adequately coordinated (selectivity of the protections). (design failure)

2. The EDG control systems (starting and coupling) must be independent of the safety 220 Vac bus bars. (design failure)

3. The malfunction of the under frequency protections was due to a faulty wiring of the phases in these protections. This was identified as a weakness in the unit's modification management process. (management failure)

This paper mainly treats the assessment for the Belgian NPPs, of the two first lessons learned concerning a design error in the electrical systems.

2 SHORT DESCRIPTION OF A BELGIAN NPP ELECTRICAL POWER SYSTEM

In the four most recent Belgian NPPs, the safety electrical systems are threefold redundant (trains B, R and G). The three trains are separated physically and electrically.

In normal operation, each electrical train is supplied by the external 400 kV network. When this preferential source is lost the 150 kV back-up network can supply the auxiliaries. In case of loss of offsite power the three EDGs start automatically and are coupled to their respective Class 1E 6 kVac bus bar.

Hereafter the general principles of an uninterruptible power supply (UPS) in the Belgian NPPs are described in general.

One UPS unit includes a rectifier, an inverter, a battery and a by-pass transformer. In some cases, the rectifier and the battery supply not only the inverter but also other 110/115 Vdc loads. Under normal operation, the inverter power supply is ensured by the rectifier in parallel with the battery. In the event of external electrical transient (house load operation, grid overvoltage,…), and if the rectifier is tripped, the inverter remains supplied with the battery, thus maintaining without any interruption the supply of the Class 1 E 220Vac loads. If the inverter fails, the swing towards the by-pass transformer via the static switch also ensures the supply of the Class 1E 220 Vac loads. In this case, if a black-out occurs later, the 220 Vac loads are no more supplied until the diesel is coupled to the 6 kVac bus bar (they are out of voltage during around 10 s).

3 BEL V REQUESTS TO THE LICENSEE

Following the incident of Forsmark 1, several questions were asked by the Belgian Safety Authorities (FANC[1]) to the licensee, and an analysis of the situation in the Belgian NPPs was carried out by the licensee. Meanwhile the Belgian TSO (Bel V) made an independent evaluation of this situation.

On the basis of this evaluation and in agreement with the FANC, Bel V has firstly asked the licensee to plan and carry out the following actions, for all the units of the sites of Tihange and Doel :

1. The licensee should confirm that during an overvoltage transient the rectifier (and not the inverter) should trip so that the Class 1E 220 Vac bus bar remains supplied by the battery via the inverter.
2. The required selectivity should be demonstrated on the basis of the overvoltage protection values set up in the rectifier and the inverter.
3. Testing should be carried out with a representative equipment submitted to the most conservative overvoltage transient to validate the demonstration.
4. The licensee should verify and confirm that periodic testing of the rectifier/inverter protections are planned and correctly implemented.
5. The Safety Analysis Report (SAR) must be supplemented to describe correctly the design principles related to the protections of such an equipment.

After discussion with the licensee, complementary actions were detailed and asked by Bel V:

- The licensee should give more justification to confirm that the EDG control systems are fully independent from the uninterruptible and backed-up Class 1E 220 Vac bus bars.
- The licensee should check that the Class 1E 220 Vac distribution grid is dimensioned in accordance with the original design bases. It should be guaranteed that no deviations from the design, detrimental to the good performance of the installations, have been observed during the last operation.
- The licensee should determine and justify the most conservative overvoltage transient for the Belgian NPPs, that must be considered as the reference for the tests of the representative equipment.
- The licensee should propose modifications to the installations if a deviation from the design or an anomaly during the overvoltage transient tests is observed.

4 THE LICENSEE ACTION PLAN

In order to meet the Bel V requests, the architect engineer (Tractebel) established an action plan , on behalf of the licensee, with the following steps.

4.1 Evaluation of the overvoltage transient

To determine the overvoltage transient to be applied to the rectifiers/inverters, various supply configurations of the internal distribution network were analyzed.

- Auxiliary equipments supplied with the external grid: either the 400 kV network with the main generator uncoupled from the grid, or the 150 kV network, whatever the state of the unit.

[1] FANC : Belgian Federal Agency of the Nuclear Control

- Auxiliary equipments tapping from the main generator, during the normal operation of the unit, generator coupled with the grid.
- Auxiliary equipments tapping from the main generator, the generator being uncoupled from the grid (“house load operation”).
- Transient operation: house load operation after elimination of a short-circuit or with a high reactive power.

Amongst these four situations, the most conservative overvoltage transient is the house load operation after elimination of a short circuit[2] or with a high reactive power. In this case, the architect engineer has evaluated that the highest voltage remains lower than 135 % of the rated voltage of the main generator (limited by the characteristics of the generator). Taking into consideration different factors (saturation of the transformers and motors, other voltage drops), the 6 kV bus bars will be subjected to an overvoltage of 130 % Un.

The *most conservative overvoltage transient* to be considered for the Belgian NPPs consists of a fast rise of voltage (during 40 ms ≤ T ≤ 50ms, two periods at two periods and half with 50 Hz) from 80% to 130% Un, this latter maintained during 3 s. The voltage returns then in the normal operating range, between Un +10% and Un -15%.

4.2 Behaviour of the rectifiers/inverters during an overvoltage transient

4.2.1 Analysis of the documentation

For each unit the following technical data related to the rectifier and the inverter were illustrated on a synthetic diagram:

- The name of the manufacturer and the type of equipment
- The undervoltage and overvoltage protections (thresholds and delays)
- The input/output voltage range for the normal operation

All this information was analysed and used by the architect engineer to determine the capability of the UPS to whithstand an overvoltage transient and to evaluate the suitability of the selectivity of the protections between the rectifier and the inverter during such a transient.

4.2.2 Testing of representative equipment

In 2007, several types of UPS were tested with the rectifer and/or the inverter (or the inverter logic command). When the testing was not possible the manufacturer has given a technical advice. Some older equipment cannot be tested because of obsolescence (neither manufacturer nor similar material available).

The equipment to be tested was subjected to the most conservative overvoltage transient justified for the Belgian NPPs.

Following the architect engineer the tests have allowed to verify that the DC voltage regulation of the rectifier is sufficiently efficient (time of regulation lower than 300 ms), after an overvoltage transient, to maintain the voltage within the allowed limits or to bring it back before the activation of the rectifier/inverter protections. The DC overvoltage value following

[2] Close to the Forsmark event.

the overvoltage transient at the rectifier input was almost identical for all the tested equipment. For the tested inverters no significant perturbation was observed at the inverter output.

4.2.3 Proposals of modifications

Based on the analysis and the test results, the licensee / architect engineer concluded that no modification of the design was needed in the 7 Belgian NPPs to face an overvoltage transient like a "Forsmark" transient. There was no risk of tripping the inverter during an overvoltage transient defined for the Belgian NPPs, that can be considered as a CCF[3], when all the equipment work correctly.

However, the architect engineer proposed some modifications of the rectifiers/inverters to improve the defence in depth of the safety electrical installations in case of a single failure. For example, the selectivity of the overvoltage protections should be adapted to avoid the trip of the inverter in case of failure of the associated rectifier. This failure must be considered as a single failure and not as a CCF like the "Forsmark" transient.

4.3 Independence of the EDG control systems from the Class 1E 220 Vac bus bars

4.3.1 Tihange 1, 2 and 3 NPPs

Under the most conservative overvoltage transient which would involve the loss of the normal supply of the normal and Class 1E 6 kV bus bars as well as the loss of a Class 1E 220 V CA inverter, the startup and coupling of the EDG would proceed normally. They are independent of the Class 1E 220 V CA bus bar.

The analysis of the diagrams also showed that:

- The shedding sequence is automatic and independent of the Class 1E 220 Vac source.
- The reloading of the Class 1E 380 Vac motors is automatic and independent of the Class 1E 220 Vac source.
- The automatic load sequence for the Class 1E 6 kV loads, which depends on the Class 1E 220 Vac source, would proceed normally because this source would be re-supplied immediately by the by-pass transformer of the inverter at the time of the coupling of the EDG. There would be thus no additional time with the execution of the EDG automatic loading program.

4.3.2 Doel 1, 2, 3 and 4 NPPs

All the 1E classified control functions (such as the sequences of starting, coupling, shedding, loading, stop) and the protection functions of the 1st and 2nd levels EDGs are supplied by the Class 1E 110 Vdc (24 Vdc) bus bars in Doel 1-2 (Doel 3-4) backed-up by the associated batteries.

Independence between the EDG control and protection systems and the Class 1E 220 Vac distribution grid of all the Doel NPPs is thus assured.

[3] CCF : Common Cause Failure

4.4 Verification of the periodic testing procedures

The licensee has recorded the on site setpoint values (threshold and delay) of all the overvoltage UPS protections.
Deviations were observed between the on site set values and the values reported in the study. The study has been revised consequently.
The licensee verified and confirmed that all the UPS protections (undervoltage, overvoltage and frequency) are well verified periodically on the basis of the test procedures.

5 BELV ASSESSMENT

Hereafter the following comments are mentioned to illustrate some of the most relevant results of the Bel V assessment and to show on which level of technical details the review had to be realized.

- *2nd protection level of Tihange 2 and 3 NPPs* : the adjustment of the DC overvoltage protections at the rectifier output and the inverter input may not provide an optimal selectivity considering the delay is null for each protection and the difference between both thresholds would be insufficient during an overvoltage transient. Besides, after analysis of the voltage curves recorded during the manufacturer tests, the value of the DC voltage peak at the rectifier output was estimated higher than the actual inverter output protection value so that the trip of the inverter cannot be ruled out during such a transient.

- *1st and 2nd levels of protection of Doel 3 and 4 NPPs (2/3 trains)* : the adjustment of the DC overvoltage protections at the rectifier output and the inverter input may not provide a sufficient selectivity during a “Forsmark” transient. The thresholds values are very close (mainly in Doel 3) and because of the zero delay at the inverter input, the inverter would trip likely before the rectifier. Supplementary explanations and justifications were also asked to the licensee on the verification of the selectivity of the protections during the representative tests carried out by the manufacturer.

- *Improvement of the selectivity between the protections of rectifiers and inverters in Tihange 1 NPP in case of a single failure (e.g. rectifier) :* The representative tests for Tihange 1 showed that the rectifier voltage regulation time was very lower than the setup delays. In this case, it was concluded that no CCF can happen during a Forsmark transient. But, as the overvoltage protections of the rectifier and the inverter were adjusted at the same values (thresholds and delays), this coordination of the protections may not provide any selectivity if a rectifier fails in one train (single failure). Therefore, the licensee should improve the defence in depth of the installation regarding the single failure.

- *Possible activation of the inverter ouput AC overvoltage protection* : Bel V considered that the insensitivity of the inverter output AC voltage with the variations of the DC voltage (in case of overvoltage) was not sufficiently argued and justified on the basis of the tests carried out on similar material. The licensee should verify and justify that the inverter is not likely to trip on its output protection.

On the basis of its assessment of the licensee report, Bel V has considered that a potential risk of a trip of inverter in more than one train could not be ruled out in some units, following a “Forsmark” transient. This kind of failure should be regarded as a common mode failure (CCF), and beyond the design which considered the loss of one train only.

Given the serious consequences of the loss of the Class 1E 220 Vac in more than one train, Bel V has also requested that the concerned equipment should be adapted to make the design of the noninterruptible Class 1E 220 Vac, more robust with respect to the CCF ("Forsmark" transient) and to the single failure of some sensitive components (single failure).

6 LICENSEE SHORT AND LONG TERM CORRECTIVE ACTIONS

6.1 Short term actions

6.1.1 Tihange 2 and 3 NPPs

In order to answer the Bel V remarks, the licensee has examined in more details the electrical schemes, circuits and components of the UPS protections. On the basis of this finer analysis the licensee justified that the selectivity is sufficient between the protections of the rectifier and the inverter. Furthermore, the licensee argued that the current UPS will be replaced by new ones in the near future, taking into consideration the lessons learned from the Forsmark event.

6.1.2 Doel 3 and 4 NPPs

As no equipment was available for full-scale tests, the manufacturer has modelized the inverters with conservative assumptions and carried out various simulations of the reference overvoltage transient retained for the Belgian NPPs.
The simulations showed that the inverter input overvoltage protection could be activated during a „Forsmark" transient.
Therefore, the licensee proposed to install a delay on this protection in order to improve the selectivity between the protections of the rectifer and the inverter (2008-2009).

Before this modification can be realized on site, the licensee had to write a Justification for Continuous Operation (JCO) justifying that the unit can continue to operate without any risk for the safety of the installations. The JCO analyzed different scenarios including the loss of two Class 1E 220 Vac trains. As conclusion, a specific procedure had to be written for defining the instructions in case of loss of two Class 1E 220 Vac trains.

6.1.3 Tihange 1 NPP

In order to cope with a single failure of the rectifier, the delays and thresholds protection values were adapted in 2008 to improve the selectivity between the DC overvoltage protections of the rectifier and the inverter.

6.1.4 Non activation of the inverter output AC overvoltage protection

On the basis of the manufacturer simulations and test results, the licensee verified and justified the magnitude of the inverter regulation time in case of a "Forsmark" transient. For each inverter installed in the Belgian units, the licensee confirmed that the delay of the inverter output AC overvoltage protection is higher than the inverter regulation time. In this case, the inverter cannot trip on this protection following a "Forsmark" transient.

6.1.5 Consequences of the loss of 220 Vac voltage

The licensee realized a deeper review of the consequences on the 1st level EDG automatic load sequence. This review showed that this sequence would proceed normally except for the auxiliary feedwater pump. This pump will have to be started manually by the operator from the MCR (via 115 Vdc).

For the 2nd protection level, the EDG load sequence is not initiated when the 220 Vac voltage comes back for the units of Tihange 2 and 3 as long as the RPS of the 2nd level is not reset by the operator. Nevertheless, the safety equipment can be started manually by the operator from the 2nd level MCR (via 115 Vdc).

6.2 Long term actions

6.2.1 Replacement of the UPS equipment

Because of the obsolescence of some current UPS equipment the licensee has decided to replace them from 2009 untill 2011.

The new equipment takes into account the experience feedback from the Forsmark 1 event. The selectivity of the protections between the rectifier and the inverter has been adapted (no inverter input overvoltage protection) and a voltage limiter has been added at the rectifier output.

Each new UPS is tested and submitted to the most conservative overvoltage transient.

6.2.2 Recommendations of the CSNI Task Group

A Belgian representative is participating on behalf of the licensee to the CSNI Task Group (Sw, Be, Fr, Fi, Ge, Ja, US) related to “Defence in Depth of Electrical Systems and Grid Interaction” (started in April 2008).

The task Group has already drafted a report with several recommendations concerning the defence in depth of the safety electrical installations. This draft has been presented and commented during an international meeting (Paris) in April 2009. The Task Group has foreseen other activities to complete the conclusions of his report.

Bel V and the licensee have agreed that the final recommendations of the CSNI Task Group will be used as a reference for a future reassessment of the design of the safety electrical systems.

For instance, in this framework, various themas should be examined and discussed:

- Relationships between the nuclear licensee and the grid owner (agreement protocols, black out procedures, communication protocols between NPP and grid manager, etc.);
- Review of the electrical transients to be taken into account in the design of the safety electrical systems (confirmation of the most conservative overvoltage transient, etc.)
- Defense in depth of the safety electrical systems (design of the electrical protections, etc.)
- …

7 CONCLUSIONS AND FURTHER DEVELOPMENTS

Bel V requests were focusing on the important lessons learned of the Forsmark 1 event related specifically to the design of the safety electrical systems.

- Adequate selectivity of the UPS protections between the rectifier and the inverter, following the most conservative overvoltage transient.
- Independence of the EDG control systems from the Class 1E 220 Vac bus bars.

The licensee has evaluated these two safety concerns, justified and carried out short term corrective actions that meet Bel V requests.

As long term actions, the licensee will replace the current UPS by new ones taking into account the lessons learned from the Forsmark 1 event.

The design of the safety electrical systems will be further evaluated by the licensee on the basis of the final recommendations of the CSNI Task Group related to « Defence in Depth of Electrical Systems and Grid Interaction ».

We may conclude that the Forsmark event highlighted the lack of nuclear industry (and regulatory bodies) consideration for overvoltage transients, as opposed to degraded voltage.