Co-simulating fault events in the on- and off-site electrical system of a nuclear power plant

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Abstract—Continuous search for safety enhancements, reported events from the past and changes in the power system motivate studies on the impact of power systems in the safety of operations of nuclear power plants (NPP). The on- and off-site systems of an NPP have interactions with each other, but these are usually simulated with separate tools and with varying levels of detail.

This paper builds on previous work in developing a co-simulation platform that connects the simulation of the thermomechanical and automation systems of an NPP with the simulation of the related electrical power systems, composed of the on-site grid and the off-site grid (transmission system). This co-simulation platform enables the integration of large-scale NPP models and performance of fault-based simulations to evaluate the impacts of selected grid fault scenarios on NPP operations. This paper presents an overview of the simulation models, describes the tested fault scenarios that affect both on- and off-site electrical grids, and offers a comparison between simulation results obtained with the co-simulation platform and simulations comprising only the electrical systems, which treat the NPP as a black-box.

The presented results show the disturbance response at various system levels, allow comparison with alarms and protection function limits and assess where the co-simulation approach may be of benefit.

Index Terms—co-simulation, nuclear power, electric system, grid faults, thermomechanical system

I. INTRODUCTION

Extreme weather events caused by climate change, less predictable RES generation and a decrease in the total inertia available in the grid are key factors that will determine the quality of the future power system. Despite a high availability of grid data enabling the predictive maintenance of equipment, unexpected events are becoming more common. According to ENTSO-E statistics [1], [2], the number of grid disturbances increased in the last decade, and so did the energy not supplied (ENS) caused by these disturbances.

The changing power grid must not impede the safe operation of existing and prospective nuclear power plants (NPPs). The integration of NPP in the power grid and ensuring its safety is of utmost importance. It is also important to assess the impacts from the NPPs to the grid itself, especially considering

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II. DESCRIPTION OF THE COSI PLATFORM

The COSI platform, initially developed in MATLAB, was described in detail in a previous publication [3], therefore only key features are summarised here.

The NPP is modelled in Apros Nuclear while the electrical system, both on- and off-site, is modelled in Simulink. The Master Program coordinates the co-simulation of different software domains (Fig. 1), and connects to Apros using the Open Platform Communications (OPC) data connection protocol. The Master Program starts with simulation until it reaches a steady state or starts with saved steady state conditions to accelerate consecutive co-simulations. Simulink performs a
number of electrical simulations for a single thermomechanical simulation. The processes alternate until the co-simulation end time is reached.

For co-simulation purposes, electrical simulation for certain components (generator, transformers, circuit breakers, electric motors, etc.) in Apros is disabled. Section III-B provides information about which parts of electrical system are simulated in Simulink.

III. BASIC MODELS AND FAULT SCENARIOS

This section introduces the NPP model, on- and off-site electrical grids, and fault scenarios in a general manner. All mentioned items are important for successful and meaningful co-simulations. The COSI platform is able to use existing Apros and Simulink models, so only minor improvements were made in the available NPP (Apros) and on-site grid (Simulink) models, which were kindly provided by project partners.

A. Basic NPP model

The NPP model (Apros) represents a typical large-scale pressurized water-reactor (PWR) NPP unit of several hundred MW generation capacity. The NPP unit contains the reactor, high- and low-pressure turbines, reheaters and moisture separators, turbine shafts, two generators, and control and electrical systems. Moreover, there are main and backup connections to the transmission grid.

The main interface between the thermomechanical (Apros) and electrical (Simulink) simulations are the generator and pump sets. These components are present in both thermomechanical and electrical models. In a co-simulation, the generator feeds rotational speed and electrical power from the electrical simulation to Apros. Apros then returns the mechanical power that the turbine and shaft deliver back to the electrical simulation as an input to the generator model.

This NPP model includes two types of pumps, basic and common. The pumps are co-simulated in a similar manner as the generator but with the pumps, the electrical simulation provides speed as output and receives mechanical torque as input.

B. On-site grid

The on-site electrical grid (Simulink) includes a unit transformer, an auxiliary transformer, one generator with a voltage regulator and exciter (IEEE type 1), primary circulation, feed water, circulating water, service water, main condensate, and normal make-up and drain pump sets. In addition, there are MW-sized loads connected to the 6.3 kV voltage level plus safety and auxiliary process loads fed through 6.3/0.4 kV transformers. Almost all the above mentioned items are coupled together between Apros and Simulink, with only a 6.3 kV level load, and safety and auxiliary process loads (0.4 kV) not being integrated in the co-simulation. In addition, the on-site grid model includes measurement points at different voltage levels so results can be stored. Fig. 2 illustrates the on-site electric grid model.

As shown in Fig. 2, the on-site electrical grid model does not include backup connections to the transmission grid or diesel generators. This necessitates some simplifications in the fault scenario implementations.

Table I presents limits for alarms and protection functions in the on-site grid.

<table>
<thead>
<tr>
<th>Function</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator frequency alarm</td>
<td>f &lt; 49 Hz</td>
</tr>
<tr>
<td>Grid disconnection</td>
<td>f &lt; 46.9 Hz</td>
</tr>
<tr>
<td>Generator disconnection</td>
<td>f &lt; 46.8 Hz</td>
</tr>
<tr>
<td>Generator reverse power protection</td>
<td>Gen P &lt; -2.4 MW</td>
</tr>
<tr>
<td>Generator stator overload alarm</td>
<td>Igen &gt; 11 kA</td>
</tr>
<tr>
<td>Generator over voltage</td>
<td>Gen volt &gt; 19.7 kV</td>
</tr>
</tbody>
</table>

C. Off-site grid

The off-site grid model (Simulink) consists of a simplified model of the Finnish transmission system, at present only covering the 400 kV level. The off-site grid model was created and improved with the help of publicly available resources. Particularly beneficial resources were [5]–[10], which guided the creation of the off-site grid model. Initially, the Finnish part of a Nordic model developed in [10] was used. Then, the author of [5] provided more comprehensive data for Finland in the QGIS (open-source geographic information system) format, while online data was downloaded from Fingrid [6]–[8] and generation-related information from the Finnish Energy Authority [9].

At this point of development, the transmission grid is considered to be hybrid, as only three of the largest generators in the system are modelled with synchronous generators. All other generators are modelled with voltage sources in series with inductors and resistors. Fig. 3 illustrates a simplified version of the developed 50-node transmission grid model.

The generation nodes represent nuclear and hydro generation, the slack bus is a north-west AC connection to Sweden, and the nodal loading is close to uniform (there are a higher number of nodes in the south in the 50-node model). This represents a light summer loading scenario, when the CHP...
Fig. 2. Electrical grid model presenting necessary details of (e.g. transformer windings) system components from transmission grid to the 0.4 kV level. Different types of pump sets and number of them are indicated with numbers and decimals. Pumps surrounded by dashed lines are not co-simulated. Fault locations 3-6 are also indicated.

Further off-site grid model developments include the modelling of reactors, capacitors, power system stabilizers, HVDC connections, and incrementally swapping the remaining voltage sources with appropriately parametrized synchronous machines. However, it should be noted that the response of the transmission grid model has been compared with a Thevenin equivalent representing the transmission system from the point of view of the NPP. The Thevenin equivalent was provided by Fingrid, and to some extent confirms the general validity of the transmission model as developed thus far.

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Table II

<table>
<thead>
<tr>
<th>Location</th>
<th>LG</th>
<th>LLL</th>
<th>OPC</th>
<th>Fault profile</th>
<th>Total rate of occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>SC1, OPC1</td>
<td>Very high</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
<td>✓</td>
<td>SC1, OPC1</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>✓</td>
<td>✓</td>
<td>SC2, SC3, OPC2</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
<td></td>
<td>SC3, OPC5</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
<td>✓</td>
<td>OPC3</td>
<td>Medium</td>
<td></td>
</tr>
</tbody>
</table>

D. Fault scenarios

There are several indicators that can express how relevant a fault scenario is in the context of the simulated system. For example, the severity of fault events, the possibility for undetected faults, fault profiles, the rate of occurrence of faults, and the NPP loading level may be considered. The severity of fault events may be evaluated by expected deviations in electrical quantities (e.g. voltage) or if the fault can bring on a common cause failure, which is a consequence of a fault that disturbs several systems. This can be highly dependent on the fault location. The severity of faults and the
possibility for undetected faults were evaluated by reviewing earlier studies and reported cases [11]–[16], and by performing preliminary electrical-only simulations. Fault profiles were formed by narrowing down relevant fault types to three main types of faults, phase to ground (LG), three phases to ground (LLL[LG], if applicable) and open phase condition (OPC), and by considering various situations in the electrical grid, such as the fault, the fault clearing sequence and the NPP loading level, which was selected to be full power for this study. Fault profiles were influenced by the literature [12], [14], [16], [17], and by discussions with the project steering group.

The total rate of fault occurrence (including all types of faults) was estimated based on ENTSO-e and Fingrid historical data [2] for locations 1-3, and was based on the individual failure rate of devices, such as circuit breakers, generators and transformers, for locations 4-6 [18]–[20]. Although the fault type is often undefined in these types of data sets, such estimations can be used to compare and influence the relevance rating of each type of fault. The likelihood of the total rate of occurrence per 10 years is defined as follows: fewer than 0.1 faults – very low, more than 0.1 – low, more than 1 fault – medium, more than 10 faults – high, more than 100 faults – very high.

Relevant fault scenarios and the rate of fault occurrence at that location are summarised in Table II. Each fault type is paired with the fault profile that dictates the situation in the grid and the fault clearing sequence. Faults marked in Table II were considered relevant to be co-simulated during the project, with only the fault profiles marked in parenthesis presented in this paper and Table III.

IV. SIMULATION RESULTS AND COMMENTS

This section presents the simulation results for locations 2-4 with the presented on- and off-site models and fault scenarios. See Fig. 2 for the measurement block locations. Pure electrical simulation (Simulink) and co-simulation results for frequency, generator active power, generator stator current, generator terminal voltage and currents of one pump type are included. The simulations were run for 12 seconds originally, but only 10 seconds are presented for better visualization.

Fig. 4 illustrates the frequency results with varying fault location and fault profile combinations. As shown in the figure, the results between the purely electrical simulation and the co-simulation do not differ much, except in case Location 2 LG, where the frequency keeps oscillating slightly with the co-simulation. In case Location 2 LLLG the simulated system becomes unstable but in the other cases the system is able to sustain the disturbances. Furthermore, the frequency only exceeds the limits (Table I) in case Location 3 LLL, if the unstable case is not considered. Generator active power results are presented in Fig. 5, which shows that the location 3 cases remain stable after the fault, but all of them show different responses to the fault. Case Location 3 LG recovers to close to the initial power level and cases Location 3 LLLG and Location 3 OPC show a decrease in power to close to zero (co-simulation). The power in case Location 3 OPC decreases faster than in case Location 3 LLLG, mainly due to differences in the fault profiles, as in Location 3 OPC the generator is disconnected from the grid and in Location 3 LLLG the simulated process (in Apros) decreases the power level. Cases Location 2 LLLG, Location 3 LLLG and Location 4 LLL exceed the generator reverse power limit of -2.4 MW (Table I). The power system stabilizer (PSS) is not part of the model and it is expected that a PSS would dampen out the enduring oscillations that can be seen clearly in Location 2 LG in Fig. 5. Location 4 LLL shows interesting generator behaviour (co-simulation), as after the fault the active power first decreases almost to zero, and then at around 6 seconds recovers to close to its initial value and stabilizes. However, an additional simulation run for 24 seconds (not presented here) shows that the active power starts to oscillate again and becomes unstable.

Generator stator currents are presented in Fig. 6. As shown
TABLE III
FAULT PROFILES. FAULT PROFILES VARY ACCORDING TO THE SIMULATED FAULT TYPE, LOCATION AND FAULT CLEARING SEQUENCE.

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault profile</th>
<th>Locations</th>
<th>Description of the situation in the grid, fault, and fault clearing sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short circuit</td>
<td>SC1</td>
<td>Location 2</td>
<td>Backup protection case. Backup fault clearance of busbar and line faults, with fault duration of 500 ms. Before the fault one bus is out of operation. The bus protection is supposed to fail to operate and the fault is cleared by remote zone 2 distance protection. Adapted from [17].</td>
</tr>
<tr>
<td>Short circuit</td>
<td>SC2</td>
<td>Location 3 and 4</td>
<td>Backup protection case. Backup fault clearance of busbar and line faults, with fault duration of 250 ms. Off-site, this illustrates a fault with duration equal to the fault-ride-through requirement as stated by the grid code. On-site, this fault illustrates the case where the protection devices fail to operate properly.</td>
</tr>
<tr>
<td>OPC</td>
<td>OPC2</td>
<td>Location 3</td>
<td>Normal protection case. Trip of the circuit-breaker (200 ms). Disconnect generator and/or disconnect line. Switch supply to back-up connection. Use of emergency diesel generators if imbalance persists.</td>
</tr>
</tbody>
</table>

in the figure, the generator stator currents surpass the limit (11 kA) in all cases except in case Location 3 OPC, where the generator is disconnected. Cases Location 2 LG, Location 3 LG and Location 3 OPC show significant current imbalance during the fault. The differences between the results with and without co-simulation are similar to the differences observed in the generator active power results. Fig. 7 illustrates the generator terminal voltage results for the various cases. As presented, only in case Location 2 LLLG is the generator terminal voltage greater than the limit of 19.7 kV (Table I). Differences between the co-simulation and Simulink simulation are quite small, which is logical, since the NPP generator excitation system is simulated in Simulink in both cases. The primary circulation pump (Pump 1.1) currents are shown in Fig. 8. Maximum currents are 1.2, 2.6, 1.6, 4.5, 2 and 3.5 times the nominal current with cases Location 2 LG, Location 2 LLLG, Location 3 LG, Location 3 LLLG, Location 3 OPC and Location 4 LLL, respectively. Current imbalance is significant with cases Location 2 LG, Location 3 LG and Location 3 OPC. Additionally, differences between the co-simulation and pure electrical simulation are quite small. Pump 1.1 torque results are presented in Fig. 9. As shown in the figure, there is a small offset in all cases, which is caused by different pump parameters in Simulink and Apros. During the fault, the

Fig. 6. NPP generator stator currents with presented fault scenarios.

Fig. 7. NPP generator terminal voltage with presented fault scenarios.

Fig. 8. Pump 1.1 (type common pump) currents with presented fault scenarios.

Fig. 9. Pump 1.1 torque with presented fault scenarios.
differences in pump responses with and without co-simulation are quite small. After the fault, the results start to differ, as in case Location 2 LG the co-simulation keeps oscillating. Also, in case Location 3 OPC the torque with co-simulation starts to decrease and without co-simulation levels out. This is caused by the simulated process in Apros.

Fig. 9. Pump 1.1 (type common pump) torque with presented fault scenarios.

V. CONCLUSIONS

This paper expands on the concept of utilizing a multi-domain co-simulation environment for assessing the impacts of faults in the on- and off-site electrical grids on the thermomechanical processes of a NPP.

The main contribution of this paper was the inclusion of a real NPP model and the simulation of relevant fault scenarios. Several types of faults, the situation in the grid and fault clearing sequences were studied. In order to facilitate the co-simulation of fault scenarios in the off-site grid, a 50-node transmission system model was developed. This model captures the dynamic behaviour of generation rather accurately and also enables future studies concerning the changing generation and demand, and potential loss of inertia, in the power system.

Future work includes further enhancements in the on- and off-site system model, longer duration faults, e.g., loss of generation or voltage instability conditions together with different transmission system scenarios. In addition, the COSI platform could be migrated to an open source platform.

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REFERENCES


