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Electrical and Thermomechanical Co-Simulation Platform for NPP

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Abstract: In order to analyze the safety of nuclear power plants (NPP), interactions between thermomechanical and automation processes, the on-site electrical grid, and the off-site transmission system should be studied in detail. However, an initial survey of simulation tools used for the modelling and simulation of NPP shows that existing simulation tools have some drawbacks in properly simulating the aforementioned interactions. In fact, they simulate detailed electrical power systems and thermomechanical systems but neglect the detailed interactions of the electrical system with thermomechanical and automation processes. To address this challenge, this paper develops an open-source co-simulation platform which connects Apros, a proprietary simulator of the thermomechanical and automation processes in NPP, to power system simulators. The proposed platform provides an opportunity to simulate both the electrical and thermomechanical systems of an NPP simultaneously, and study the interactions between them without neglecting any details. This detailed analysis can identify critical faults more accurately, and provides better support for probabilistic risk analyses (PRA) of NPP. To investigate the effectiveness of the proposed platform, detailed thermomechanical and electrical models of an NPP, located in Finland, are cosimulated. The preliminary results emphasize that neglecting the detailed interactions between domains of NPP may lead to inaccurate simulation results and may affect NPP safety.

Keywords: cosimulation; electrical system; thermomechanical system; nuclear power plant safety

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1. Introduction

A holistic model of nuclear power plants (NPP), or generally, any type of thermal power plant, includes several domains with fundamentally different natures, such as thermomechanical loops, physical reactor models, automation and control models, an on-site electrical system, and an off-site transmission power system. From a conceptual point of view, this means that NPP should be considered as systems-of-systems.

Each of these domains has a very different nature (continuous, discrete, stochastic, etc.), with different modelling assumptions. In this regard, significant efforts have been devoted to developing multidomain simulation environments. Among them, Apros, a comprehensive software product for modelling and dynamic simulations of power plants, developed by VTT and Fortum [1], is one of the successful, and has been used in more than 30 countries for numerous projects over the last 30 years. Although Apros is a powerful multidomain simulation environment, especially with regard to the thermal process, nuclear reactor, and automation, its ability to model different dynamic events in power systems, e.g., asymmetrical faults, is limited. The same challenge can be seen in other multidomain simulation environments used for NPP, e.g., CASL VERA [2] and Salome [3]. Although these multidomain simulation environments make it possible to study the interactions among certain domains, such as mechanical, thermohydraulic, and neutronic, their ability to model and simulate events in the electrical systems is inadequate.

In general, developing a multidomain simulation environment that supports all of the necessary domains is not a trivial undertaking, due to the significant effort and expertise required. Models from different domains often need to be dealt with using a different time scale, a model of computation (MoC), and specialized solvers. Building a simulator capable of providing the appropriate environments, correct MoC and solvers, and properly coordinating them internally, is expensive and may not be worth the effort [4,5]. Furthermore, domain-specific tools are usually equipped with validated component libraries for that domain, and the correctness of models is verified by domain experts. Owing to these challenges, there is currently no systematic way to precisely study the interactions among the different domains of NPP and to analyze the effect of these interactions on the safety of the NPP.

On the other hand, disturbances in electrical systems, both on-site and off-site, may influence the performance of a thermomechanical system and lead to critical events. Analyses of operating experience are important for safety enhancements of an NPP, but should not be limited to domain-specific events. In this regard, scenarios involving loss of off-site power, or loss of off-site power combined with an emergency diesel generator common cause failure (station blackout), are not sufficient for the design of a comprehensive system. The plurality of disturbances in electric systems must be taken into account. Recent changes in electrical grids, such as the increased role of renewable energy sources with high uncertainty in their production, more frequent extreme weather conditions, a high share of electronic converters, and the implementation of digital control systems for electric systems, mean that previous design philosophies may no longer be adequate for safety analyses.

Therefore, recently, some research projects, such as the NVEC (NVEC: Nuclear Virtual Engineering Capability) project [6] in the UK and the COSI (COSI: Cosimulation model for safety and reliability of electric systems in flexible environment of NPP) project, founded by SAFIR 2022 in Finland, have considered the use of cosimulation environments to study the interactions among electrical and thermomechanical systems in NPP. This paper summarizes the achievements of the COSI project and uses existing domain-specific simulation tools as the basis for the development of a cosimulation platform. The proposed cosimulation platform is tested using a detailed thermomechanical and electrical model of an NPP located in the Nordic region. Due to the confidentiality of the data, this NPP is named "NPPX" hereafter. By comparing the cosimulation and the domain-specific simulation results in the NPPX, it is shown that some faults in the electrical system may lead to an unstable condition in the thermomechanical system, while they would not be considered critical events without the cosimulation platform.

The rest of this paper is organized as follows: Section 2 describes existing simulation environments in NPP and introduces the proposed cosimulation; Section 3 defines the architecture and implementation of the cosimulation platform; Section 4 compares the cosimulation and domain-specific simulation results in the NPPX; finally, Section 5 concludes the paper.

2. NPP Simulation Environments

2.1. Existing Simulation Environments

Figure 1 shows a diagram of a typical pressurized-water reactor (PWR) [7], while Figure 2 shows a typical electrical diagram of an NPP according to the IAEA safety standard [8]. These thermomechanical and electrical diagrams are coupled by turbine/generator and motor/pump sets, as shown in these figures. The turbines provide the mechanical torque to rotate the shafts of the generators; in the same way, motors provide electrical torque to move the shafts of the pumps. Under these circumstances, any unforeseen event in either system may change the electrical or mechanical torque of motor/pump sets or turbine/generator sets, and consequently, the rotating speed. Therefore, disturbances in one system will transfer through the coupling to another system and may challenge NPP safety.

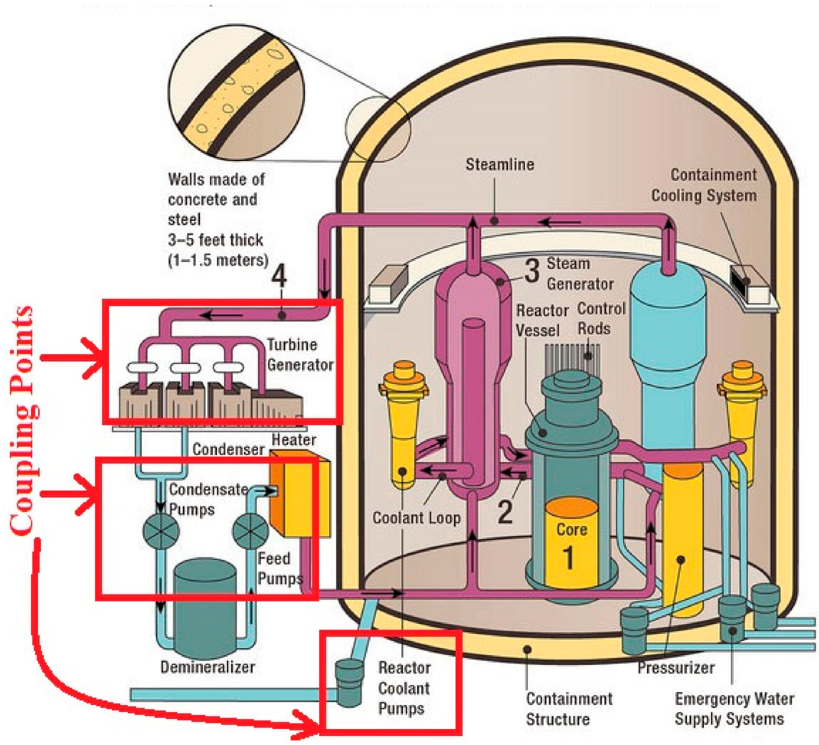

Figure 1. Typical thermomechanical diagram of a PWR [7].

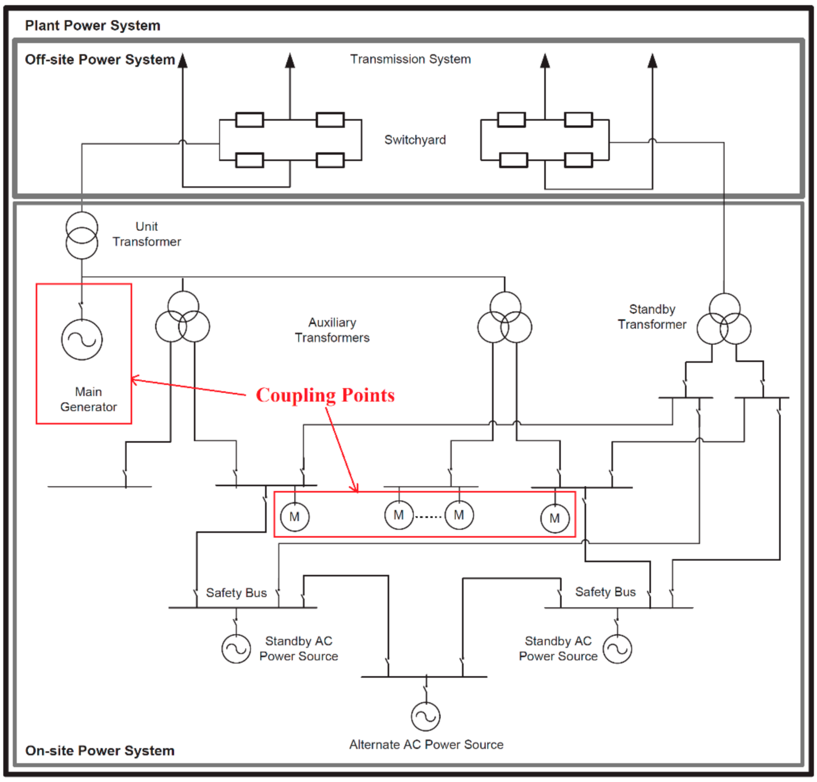

Figure 2. Typical electrical layout of an NPP based on the IAEA safety standard [8].

In order to illustrate this challenge more precisely, the mathematical model of a three-phase induction motor is briefly reviewed. If the input voltage has a sinusoidal shape, the electrical torque (T_e) can be calculated by solving the flux equation as follows [9]:

$$\frac{d}{dt}\begin{bmatrix} \lambda_{sd} \\ \lambda_{sq} \end{bmatrix} = \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} - R_S \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} - \omega_{da}\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \lambda_{sd} \\ \lambda_{sq} \end{bmatrix} \tag{1}$$

$$\frac{d}{dt}\begin{bmatrix} \lambda_{rd} \\ \lambda_{rq} \end{bmatrix} = \begin{bmatrix} v_{rd} \\ v_{rq} \end{bmatrix} - R_r \begin{bmatrix} i_{rd} \\ i_{rq} \end{bmatrix} - \omega_{dA}\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \lambda_{rd} \\ \lambda_{rq} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} = \left(\frac{1}{L_m^2 - L_r L_s}\right)\begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \end{bmatrix}\begin{bmatrix} \lambda_{sd} \\ \lambda_{sq} \\ \lambda_{rd} \\ \lambda_{sq} \end{bmatrix} \tag{3}$$

$$T_e = pL_m\left(i_{sq}i_{rd} - i_{sd}i_{rq}\right) \tag{4}$$

where λ, v, and i are respectively the flux, voltage, and current of the motor; ω is the rotating speed; subscripts r and s represent the motor and stator, respectively; subscripts d and q represent the direct and quadrature axes; L is the inductance: L_m is mutual inductance between rotor and stator; and p is the number of pole pairs. These equations show that the electrical torque is a function of the motor parameters, speed, and the working point of the electrical system, such as the voltage at the motor terminal. At the same time, the motor speed (ω_m) is a function of mechanical and electrical torque, as shown in the following equations, the so-called swing equations:

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(T_e - T_f - F\omega_m - T_m\right) \tag{5}$$

$$\frac{d\theta_m}{dt} = \omega_m \tag{6}$$

where J is the inertia of the pump/motor, F is the friction of the motor and load, T_m is the mechanical torque of the load, T_f is the shaft static friction torque, and θ_m is the mechanical angular position.

The input mechanical torque of the motor is the output hydraulic torque of the pump. Therefore, the swing equations couple the electrical model of the motor to the mechanical model of the pump. The hydraulic torque in a pump is a complex function of the pump head (H) and volumetric flow (VF) in the pump. The head in the pump depends on the flow of the thermomechanical loop and the speed of the motor/pump, as shown in the following equation:

$$H = \left(H_{max} - (H_{max} - H_{nom})\frac{VF^2}{VF_{nom}^2}\right)\left(\frac{\omega}{\omega_{nom}}\right)^2. \tag{7}$$

In summary, calculating the rotating speed requires knowledge of the mechanical and electrical torque. The mechanical and electrical torque are functions of the rotating speed and working points of both the mechanical and electrical systems. Under these circumstances, a motor/pump set couples the electrical system and thermomechanical system models. Therefore, it is necessary to simulate the interaction between thermomechanical and electrical systems to study an NPP accurately. However, while current simulation tools are not able to simulate such interactions in detail, several domain-specific tools are capable of performing detailed simulations inside the domain. For instance, in order to simulate thermomechanical systems, including nuclear reactors, Apros [1], RELAP [10], TRACE [11], Flownex [12], etc., can be used. However, none of these has the ability to carry out detailed simulations of the on- or off-site power systems in an NPP. Among these approaches, Apros can simulate electrical systems to a limited extent, but this may not always be enough for safety analyses of NPP. For example, Apros cannot analyze asymmetrical faults in electrical systems. Under these circumstances, in the design and operation of the electrical grids of NPP, power system simulators, such as PSCAD [13], PowerFactory [14], PSS/E [15], and Simulink/Simscape [16] are used, even though none of them can properly simulate thermomechanical systems.

Since existing simulators do not support detailed multidomain simulations of an NPP, power system simulators tend to model the thermomechanical part of motor/pump sets by a constant or a simple relationship between the angular speed and torque, as follows:

$$T_m = k\,\omega^2, \tag{8}$$

where T_m is the mechanical torque of the pump/motor set, ω is angular speed and k is a constant, which is usually calculated from the steady-state condition. Figure 3 shows the model of a motor/pump from MATLAB/Simulink, using this typical method.

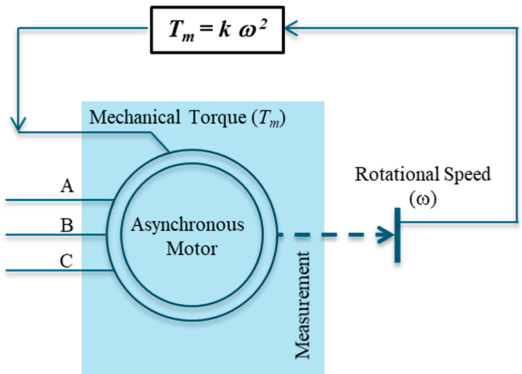

Figure 3. The typical simplified model of a motor/pump in an electrical system simulator.

This simplification has two drawbacks: (1) it is not able to assess the interactions that occur within a thermomechanical and electrical system, i.e., the impact of an electrical fault on the mass flow rate of a power plant; (2) it may lead to inaccurate results, as shown in Section 4 of this paper. In the same way, the existing methodology for modelling the on-site electrical system of NPP replaces the off-site transmission power system with a fixed Thevenin equivalent, a simplified turbine model, and neglects the detailed thermomechanical loop of the power plant, without providing a detailed model of the transmission system.

2.2. Cosimulation Environment

In order to study the detailed interactions between the electrical system (on-site and off-site grids) and thermomechanical system of NPP, a cosimulation platform needs to be developed. The cosimulation platform intends to provide an interface with which to couple the simulation tools of these different domains. In other words, the cosimulation platform provides an opportunity for each simulator to solve its model(s) independently, using its own solver, while the platform exchanges the necessary data between simulators, applying the impacts from other domains.

Using the cosimulation platform, detailed models of turbines, pumps, and all thermomechanical loops of NPP are implemented in thermomechanical simulators, e.g., Apros, while the generators, motors, and all other electrical components are modelled in a power system simulator, e.g., Simulink/Simscape. However, the cosimulation platform transfers the required variables among simulators to model the coupling of the turbine/generator sets and motor/pump sets. Thus, the impact of any event in either system (electrical or thermomechanical) will be transferred to the other, and the interactions between them can be simulated. In addition, the user can modify the models for each domain and study the results in both simulators simultaneously.

At the beginning of this research, a survey of simulation tools used by NPP operators in Nordic countries and one of the transmission system operators (TSO) was conducted in the form of interviews. It was found that Apros was used in most plants as the main process simulation tool for the thermomechanical equipment. However, for electrical simulations, various tools, including Matlab/Simulink, PSCAD, PowerFactory, NEPLAN, and PSS/E, were mentioned. Consequently, in order to develop the first version of the cosimulation platform and investigate its impact on NPP, Apros was selected as the simulator for the thermomechanical system. For power system simulation, the Simulink/Simscape toolbox was selected, because a detailed model of the electrical grid of NPPX had already been implemented in Simscape. In the future, after further analyzing the advantages of the cosimulation platform, the project will further develop the cosimulation platform to support other power system simulators, e.g., PSCAD.

3. Developing the Cosimulation Platform

In order to assess different systems using cosimulation, it is necessary to integrate the model of computation (MoC) behind a model or a simulator. The MoC represents the interactions between modules, components or phenomena; it is independent of the implementation technology (i.e., sequential or parallel) and language (i.e., Matlab, Python) [17]. The main difficulties for the integration of different MoCs involve how to deal with simultaneous events and zero-delay feedback loops. With this in mind, the cosimulation architecture design must address time step handling, and data exchange layout, interval, and protocol, which are covered in the following subsections.

3.1. Data Exchange Layout

As mentioned in Section 2, the interaction between the electrical and thermomechanical systems happens in the turbine/generator and motor/pump sets. Therefore, the thermomechanical simulator must send the mechanical power/torque of turbines and pumps to the power system simulators, while receiving the rotational speed. In addition, some control signals need to be transferred between these simulators; for example, the governor of the generators needs to send commands to valves and receive the output electrical power of the generators. More details about the proposed data exchange layout can be found in the first deliverable of the project in [18].

3.2. Data Exchange Intervals

There are different options for data exchange intervals between two or more simulators [17]. Figure 4 illustrates the different standard "data exchange" options between two simulators, i.e., *A* and *B*. Typically, parallel data exchanges are faster and allow the different simulators to operate simultaneously. Since the cosimulation of NPP has several coupling points and may be slow, running cosimulation using parallel data exchange has some advantages. This cosimulation architecture will use parallel data exchange intervals, which means, as explained in Figure 4, Apros and the power system simulator will start from initial conditions and exchange data at each time interval.

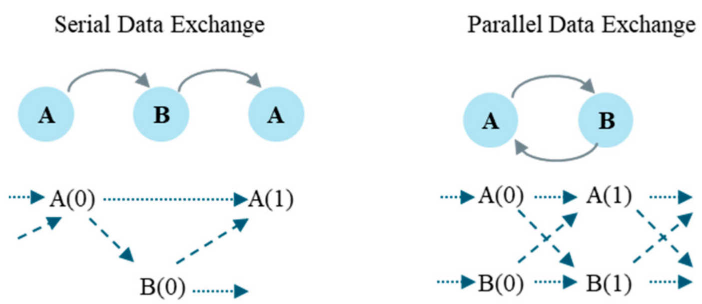

Figure 4. Standard data exchange options between two simulators, A and B.

3.3. Time Step Handling

Typically, electrical systems have faster dynamics than a thermomechanical system. Therefore, it is wise to select a shorter time step for power system simulators than in the thermomechanical simulator. Under these circumstances, during one step simulation of the thermomechanical simulator, the power system simulator must run for several time steps. Two considerations are important in the cosimulation architecture: (1) each simulator needs to select time steps which are small enough to calculate the result precisely; (2) the data exchange should happen when all simulators finish their simulation for the related time steps. Therefore, the platform must check that all simulators have completed their tasks before ending each data exchange interval.

The first version of the cosimulation platform assumed that: (1) both electrical and thermomechanical simulators have fixed time steps; (2) the time step of the thermomechanical simulator is a multiplier of the time step of the power system simulator. Using these assumptions, the data exchange interval will be similar to the time step of the thermomechanical simulator. Therefore, the cosimulation platform will exchange data between the electrical system and the thermomechanical system after each run of the simulator of the latter.

In order to accelerate the simulation speed, the platform can be developed further in future versions by handling the variable time steps. For this purpose, each simulator can select the variable time steps according to the system dynamic while the master program needs to read the duration of the next time step from the system with the slower dynamic (thermomechanical system) and set it as the stopping time for the system with the faster dynamic (electrical system).

3.4. Data Exchange Protocol

One of the main challenges in the cosimulation is creating reliable and sufficiently rapid channels through which to exchange data between the simulation tools. Each simulation tool has its own method to connect read/write to other programs. Unfortunately, there is no general protocol that all software follows. For example, Apros supports open platform communications (OPC) data connection, while PSCAD does not.

OPC is a set of interface specifications for accessing field devices within control and automation systems. It has been defined to meet the need for delivering data from hardware devices to automation systems. Despite its background, OPC can also be utilized for other communication means, such as communication between simulation tools.

In this cosimulation platform, the OPC DA (open platform communications data access) is utilized to communicate with Apros. OPC DA is an interface based on Microsoft's DCOM (distributed component object model) technology and provides OPC client functions that can be used to read and write data from the OPC server. Apros has augmented the original interface so that it can also be used to give simulation control-related commands, e.g., simulate for a predefined time forward and save the state of the simulator. These can be used by the cosimulation platform to control the entire Apros simulation environment.

The main deficiency of using OPC is that it is quite heavy, and is not the fastest way of communicating when lots of simulations need to be run quickly. Although Apros supports some faster communication interfaces, such as ACL (Apros communication library) and external model (a dynamic link library (dll) linked to Apros), these do not provide open cosimulation and can be used only in the model exchange implementation. In the open cosimulation, the user interfaces of both simulators are always visible and the user can modify the models in both domains simultaneously and analyze the results. More details about Apros and OPC can be found in [18].

3.5. The Architecture of Cosimulation Platform

As mentioned in Section 3.4, each simulator has its own data exchange protocol. Therefore, the cosimulation platform needs to have the ability to connect to different simulators using different data exchange protocols, for instance, OPC for Apros, TCP/IP for PSCAD, and so on. In addition, the platform must handle the data exchange layout, data exchange interval, a time step for each simulator, and the initialization of each simulator.

Accordingly, the architecture of the cosimulation platform consists of thermomechanical simulation tools, e.g., Apros, power system simulation tools, e.g., Simulink/Simscape toolbox, and a master program. The master program is responsible for connecting and managing all the simulation tools. Figure 5 shows the proposed architecture for this platform.

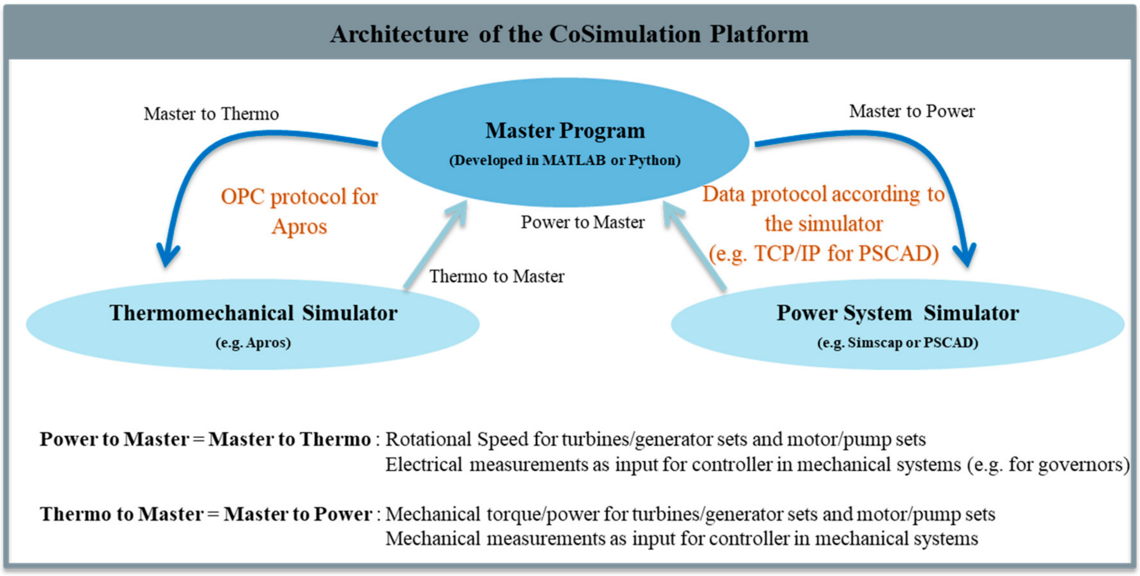

Figure 5. The proposed cosimulation architecture; arrows show data exchange.

In this architecture, the master program acts as an OPC client to read or write in Apros, which acts as the OPC server. In addition, the master program needs to support other data exchange protocols, such as TCP/IP. Therefore, it is better to develop the master program in a language support OPC and several other data protocols, such as MATLAB or Python. In the first version, MATLAB/m-file was used to develop the master program.

3.6. The Implementation of the Cosimulation Platform

Following the architecture presented in Figure 5, the first version of the cosimulation platform was developed in the COSI project. The heart of this cosimulation platform is the master program, which was developed using MATLAB/m-files environment. However, it can be developed in any programming language that supports OPC data connection, e.g., Python.

The master program connects to Apros using the OPC toolbox of MATLAB, and exchanges data and commands. The first version of the platform uses Simscape, which is a toolbox in Simulink, as the power system simulator. Using Simscape in the first version effectively eliminates the need to implement another data exchange protocol to connect to the power system simulator. However, the platform will be developed further to connect to other power system simulators in a future version, using an appropriate protocol. For instance, PSCAD can be connected using the TCP/IP protocol and the method developed in [17].

The master program has the following main sections/functions, and its detailed functionality is explained in [19].

- Set cosimulation parameters
- Define the input layout
- Create data structure and OPC HOST
- Initialising

- Cosimulation loop
- Data exchange
- Progress report and plot results

Apros can simulate pumps using three different models: basic pumps, common pumps, and motor pumps. Normally, these pump models calculate the rotation speed based on a simplified motor model combined with the pump models. However, in the cosimulation implementation, they need to accept the rotational speed as an input. Therefore, Apros pump models are upgraded and a new calculation mode is added to the new Apros version for pumps. The same approach is performed for the turbine and shaft, which need the rotational speed as an input.

The developed cosimulation platform can be found as an open-source code in [20]. The platform was developed to be user-friendly, in that the user of the cosimulation platform does not need to change the code or Apros model. The user just needs to define the input layout, i.e., to determine which turbine/generator sets or motor/pump sets will participate in the cosimulation. The open-source platform, which is freely available in [20], consists of a simple example to show how the platform can be used.

3.7. Validation and Verification

One of the advantages of developing a cosimulation platform compared to a multidomain simulation environment is the validation and verification process. The cosimulation platform does not develop new mathematical models for physical components, such as motors or pumps. The cosimulation platform uses existing models, already developed in different simulation tools, and couples them virtually, so they can work together. Under these circumstances, there is no need to validate the models and verify their accuracy by comparing the numerical results of the simulated model and measurements of the physical system. Since the simulation tools and their model have already been verified, the validation and verification process in the cosimulation platform is limited to the accuracy of the communication between the simulators. In other words, the cosimulation platform can be verified by looking at the similarity of the exchanged variables, which is defined in the data exchanged layout (see Section 3.1) in different simulators.

For instance, when the proposed platform cosimulates a motor/pump set, the motor is modelled in Simulink and the pump is modelled in Apros. Apros gets the rotating speed from Simulink through the master program and calculates the hydraulic (mechanical) torque, which is sent to Simulink, through the master program. The exchange variables are the rotating speed and the mechanical torque, which are the output of one simulator and the input of the other. In order to verify this cosimulation, it is enough to check if the exchange variables are the same in all simulators. Note that since the time step of each simulator can be different, the resolution of the exchange variable curves are different from one another.

4. Cosimulation Results

To investigate the impact of the cosimulation platform, a detailed model of an NPP located in the Nordic region is used. As mentioned earlier, for reasons of confidentiality, the NPP is referred to as NPPX. The operator of NPPX uses Apros to simulate the thermomechanical models, while MATLAB/Simulink and the Simscape toolbox are used to simulate the electrical system. In this electrical model, the off-site electrical system (transmission power system) is modelled by a fixed Thevenin equivalent. The fixed Thevenin equivalent is sufficient for basic study only; it is not suitable for study of the detailed effects of a fault in the transmission system in a NPP. Additionally, to model the on-site electrical system (without cosimulation), the pumps are modelled by a variable torque ($T_m = k\,\omega^2$), as shown in Figure 3.

However, in the cosimulation, the electrical models in Simscape are virtually coupled to the thermomechanical model of Apros using the proposed cosimulation platform. Since the detailed models are confidential, this paper presents some results to show the impact of the cosimulation platform and explains them using the typical diagram of an NPP, shown in Figures 1 and 2.

A single-phase fault is simulated in the secondary side of the auxiliary transformer, where most of the large motor-pump sets are connected (See Figures 1 and 2). It is important to note that the main aim of this simulation is to show the impact of the cosimulation in the results. Therefore, the detailed behavior of the protection system, which must be designed to clear the fault, is not investigated. In order to have a well-designed protection system, the designer first needs to simulate the fault in detail to set the protection correctly. Here, two scenarios have been simulated: (1) without cosimulation, using ($T_m = k\,\omega^2$), which is marked by Elec Simulator in the figures; and (2) using the proposed platform.

The single-phase fault at the motor terminals gives rise to imbalanced voltages, which change the electrical torque of the motors. Figure 6 shows the three-phase voltage when a single-phase fault occurs on phase a, at t = 2 s after the steady-state initial condition is achieved. It is worth mentioning that the auxiliary transformer has a Dyn connection, which is grounded with fairly high resistance.

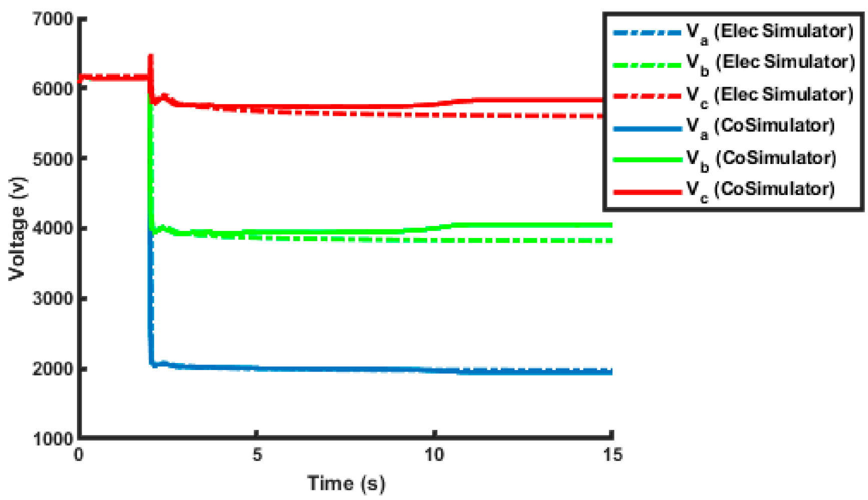

Figure 6. The phase voltages at the motor terminals; single-phase fault at t = 2 s.

Although before the fault, the voltages are similar with and without cosimulation, the cosimulation results will be slightly different after the fault occurs, as shown in Figure 6. The reason for this is that while the simplification of the entire thermomechanical system by $T_m = k\,\omega^2$ may provide acceptable accuracy in the nominal steady-state condition, it does not behave in the same way in dynamic situations. Calculating the accurate voltage would be very important when setting the protection level, especially to protect against voltage imbalances.

Among several motors connected to the on-site electrical system, two motor/pump sets (1.2 MW and 2 MW) were chosen for investigation in this document. The electrical parts of these sets (motors) are modelled using the asynchronous machine block in Matlab/Simulink, while the mechanical parts (pumps) are modelled respectively by the basic pump and the common pump models in Apros.

The input current of the first motor/pump is shown in Figure 7. As expected, the electrical system simulator yields a significant error in the current imbalance when compared with the cosimulator results.

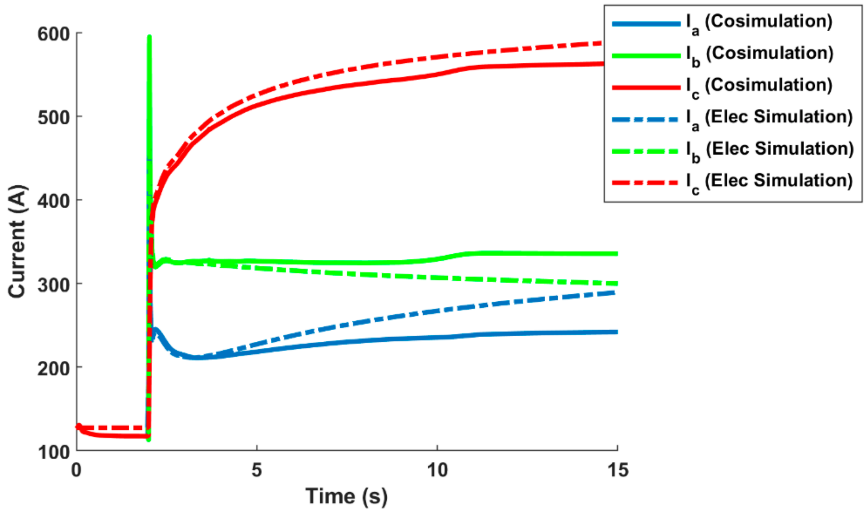

Figure 7. The input current of the first motor; when cosimulated, the motor is coupled to a common pump model connected to the NPPX loop.

This voltage and current imbalance in the motor decreases the electrical torque, and consequently, the speed and mechanical torque of the pump are reduced. Figure 8 shows the speed and mechanical torque of the 1.2 MW motor/pump set (asynchronous motor modelled in Simulink coupled to the common pump model in Apros), using cosimulation (red lines) and without cosimulation, using just an electrical system simulator, considering k = 0.2897 (blue lines).

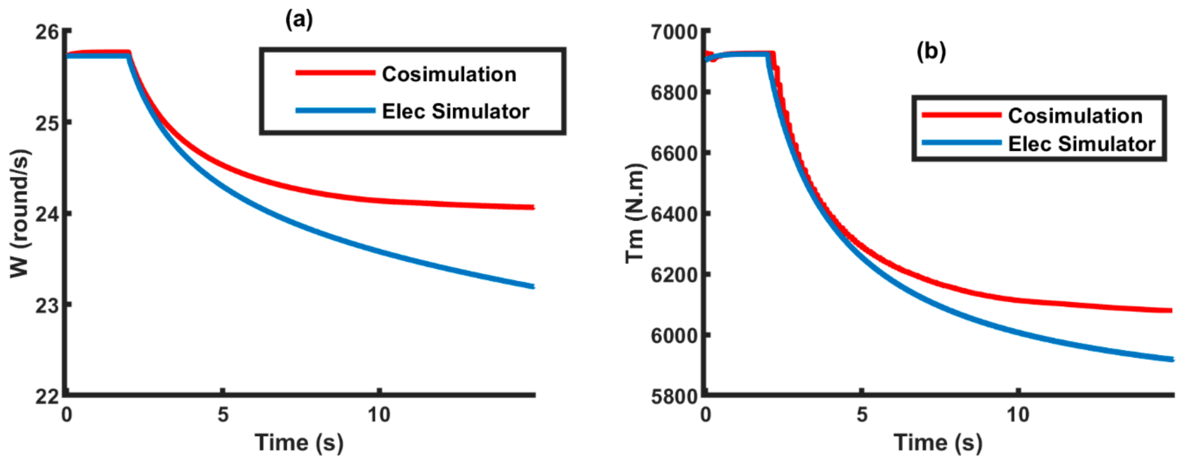

Figure 8. Simulation results of the 1.2 MW asynchronous motor, coupled to a common pump model in Apros; (**a**) speed and (**b**) mechanical torque.

Comparing the red plots with the blue in Figure 8, it is clear that these two simulators predict similar behavior. However, the numerical value of speed and torque are not the same, and using just the electrical simulator gives more conservative results, in this case, higher speed reduction. This lower speed and torque reduction in the case of cosimulation, in Figure 8, is in line with the lower average voltage reduction and input current increase, as shown in Figures 6 and 7, respectively.

The reason for this different dynamic behavior between the cosimulation and Elec Simulator is that the typical simplified model of a pump in an electrical simulator (shown in Figure 3) is not accurate enough to capture dynamic behavior. Although the factor k (in $T_m = k\,\omega^2$) can be calculated so that the nominal steady-state response of the cosimulation and Elec simulator will be identical, this precalculated fixed value will not suffice in dynamic studies.

Providing more accurate results using the cosimulation platform is not the only benefit; this platform also makes it possible to study the effect of electrical events on mechanical variables, and vice versa, which is not possible otherwise. For example, Figure 9 shows the mass flow, the output pressure, and temperature of the related pump in Apros during a fault in the electrical system.

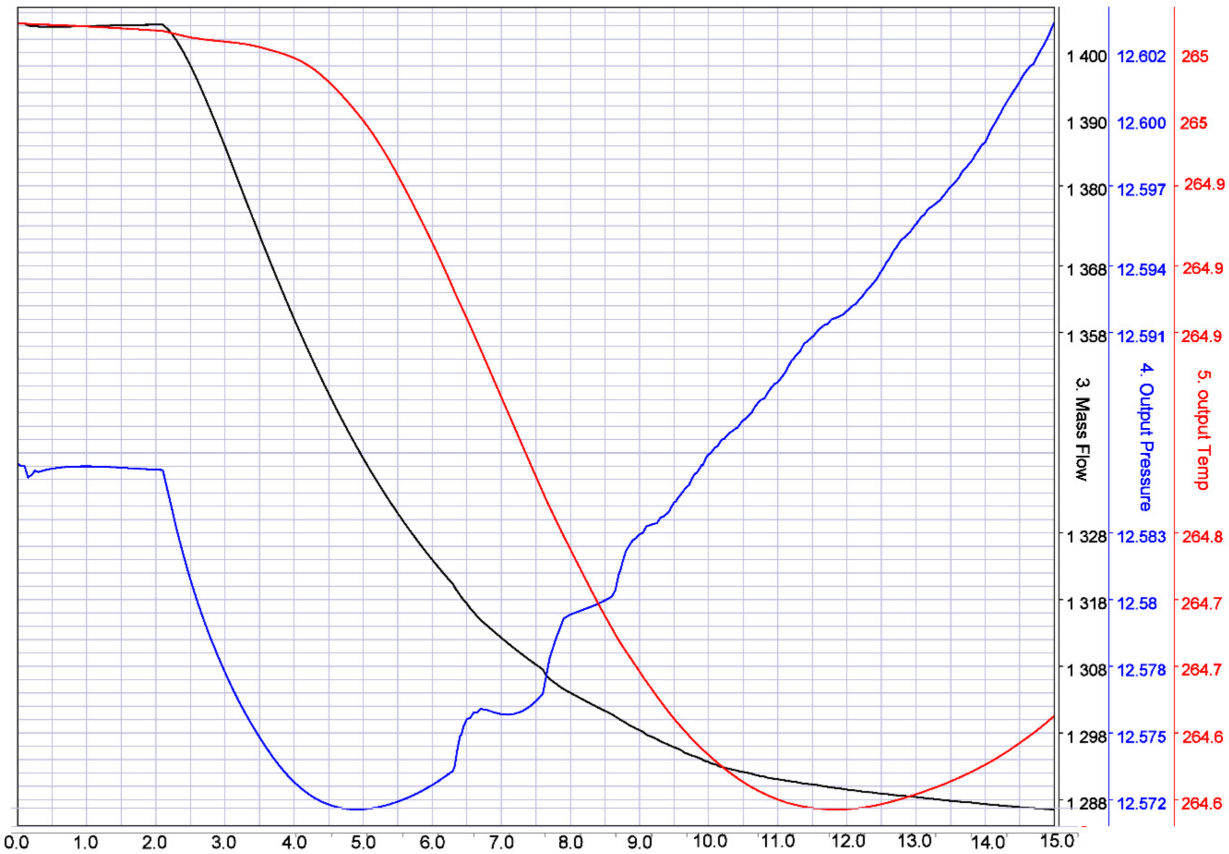

Figure 9. The mass flow, output pressure, and temperature of the related pump in Apros when a fault occurs in the electrical system.

In the case shown in Figure 8, with the simulation using just an electrical simulator, assuming $T_m = k\,\omega^2$ provides more conservative results regarding the speed and torque of the motor/pump set. However, this is not always the case. Figure 10 shows the effect of the same fault on the speed and mechanical torque of another motor/pump (a 2 MW asynchronous motor modelled in Simulink coupled to a basic pump model in Apros) using cosimulation (red lines) and without cosimulation by considering $k = 0.119$ (blue lines).

Comparing the red with the blue lines in Figure 10 shows that without cosimulation, this motor/pump set seems to be stable. The electrical simulator, neglecting the thermomechanical system, shows that the speed of the motor drops significantly, while the torque is reduced too, and the motor/pump finds a new stable condition. However, using cosimulation, the speed decreases very rapidly while the torque is initially increased. The ensuing events after fault occurrence are as follows: by reducing the voltage (see Figure 6), the speed of the motor drops, which is sent to Apros via the master program. In Apros, this motor/pump set is simulated by a basic pump, which calculates the power of the pump at the given speed. The pump power drops when the speed is reduced; however, the rate of this reduction is less than the speed reduction, and therefore, mechanical torque initially increases. This torque increase, accompanied by a reduced voltage, will lead to a faster speed reduction until the speed reaches zero. At 3.5 s, the speed reaches zero and the motor stalls. This comparison shows that while the simulation that does not consider the thermomechanical system indicates that the motor is stable, in reality, this would not be the case. It is important to note that the cosimulation will continue while the speed is negative (generator mode), but of course, the results shown in Figure 10 after the speed crosses zero (t = 3.5 s) are no longer valid.

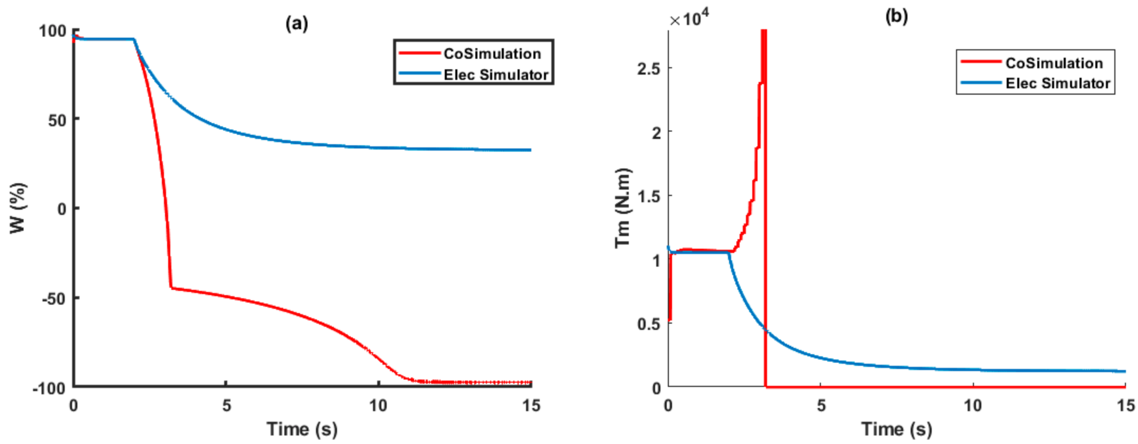

Figure 10. The simulation results of the 2 MW asynchronous motor coupled to a basic pump model in Apros; (**a**) Speed and (**b**) mechanical torque.

This example shows not only that the simulation results of the electrical or thermo-mechanical system of a NPP without considering the interaction of these two systems may not be accurate, but that they may also jeopardize NPP safety. Without applying the cosimulation, the designer or operator of NPP would not detect the instability of the above-mentioned motor/pump set.

Events in the electrical system, e.g., single-phase faults or open phase conditions, could have significant impacts on the thermomechanical system. For instance, Figure 11 shows the mass flow, the output pressure, and temperature of the pump in Apros, which is coupled to the second motor, during a single-phase fault in the electrical system. The simulation results indicate that a fault in the electrical system can lead to reverse mass flow in a very short time.

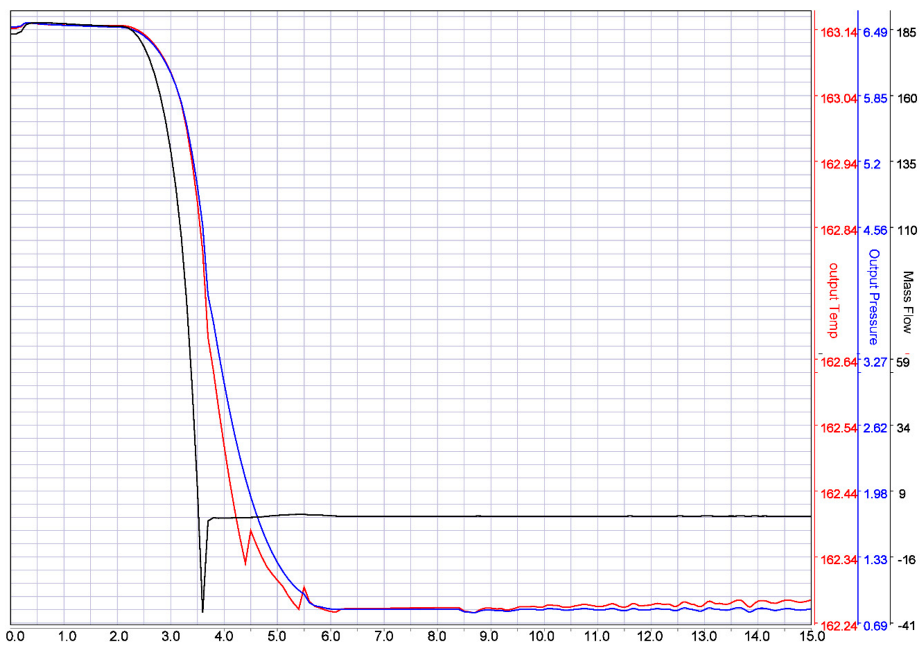

Figure 11. The mass flow, output pressure, and temperature of the second pump (2 MW) in Apros when a single-phase fault occurs in the electrical system.

It is important to note that the protection systems of NPP may detect the above-mentioned fault and react to prevent any serious event. This paper introduced a cosimulation platform, and a single-phase fault in a resistance earthed system was selected to show the importance and capabilities of the platform to support probabilistic risk analyses (PRA) of NPP.

5. Conclusions

A holistic model of thermal power plants, or more specifically, a nuclear power plant (NPP), consists of several domains, e.g., thermomechanical loops, reactor physical models, automation and control models, the on-site electrical system, and the off-site transmission power system, which are coupled. Currently, each of these systems is simulated by a domain-specific simulator, neglecting, or simplifying, the coupling among different domains. For example, the electrical system is modelled in a power system simulator, while the pumps are modelled by appling a quadratic torque-speed characteristic for motors.

However, these simplified assumptions may lead to inaccurate results. Therefore, this paper proposes a cosimulation platform with which it possible to study the multidomain composition of an NPP by virtually coupling well-known domain-specific simulators.

The first version of this platform can cosimulate an NPP when the thermomechanical system is implemented in Apros and the electrical system (on-site and off-site) is modelled in the Simulink/Simscape toolbox. The first version of this platform was developed using m-file in MATLAB and is available as an open-source platform. The platform allows the user to run simultaneously, with little effort, the electrical and thermomechanical simulators, which are coupled virtually by the cosimulation platform, and follow the results from the environments of both simulators.

The simulation results of an NPP with a detailed thermomechanical and electrical model, using the developed cosimulation platform, highlight the fact that the existing simplification assumptions and neglect of the interactions between electrical systems and thermomechanical systems can misrepresent electrical and thermomechanical behavior in the event of an electrical fault. While well-designed protection systems would likely protect the system from the fault-type treated in this paper, it is of obvious benefit to accurately model the NPP, including the thermomechanical system and its related electrical systems, as accurately as possible. Therefore, it is necessary to consider the impacts of other domains when investigating the results of any fault or event, and more study is needed to identify and investigate safety-related events using this cosimulation platform, as part of ongoing work to ensure the safety of nuclear power stations.

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