Applied co-simulation of intelligent power systems: implementation, usage, examples

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Abstract

Smart Grids link various types of energy technologies such as power electronics, machines, grids, and markets via communication technology, which leads to trans-disciplinary, multi-domain system. Simulation packages for assessing system integration of components typically cover only one sub-domain, while terribly simplifying the others. Co-simulation overcomes this by coupling sub-domain models that are described and solved within their native environments, using specialized solvers and validated libraries. This article discusses the state of the art and conceptually describes the main challenges for simulating intelligent power systems. Part 1 covers fundamental concepts, part 2 applications.

Index Terms

smart grids, co-simulation, power system simulation, HIL, intelligent electrical power system, VSC-HVDC, ICT

I. Introduction

Recent developments in information and communication technology (ICT) architectures, the massive installation of distributed energy resources (DER), and the emergence of demand-side energy management instruments have lead to a rapid deployment of smart grids [1], [2]. The corresponding coupling of power grids with various other systems, which on occasion can be of an entirely different nature, opens a wide range of mutual interaction opportunities, for example, energy storage options in gas or heat networks. The merits of the evolution towards intelligent electrical power systems are evident: the higher controllability of the electric power system potentially fosters its reliability, general operability, and benefits the electricity market.

The operating service of power system assets commonly spans several decades. A specific challenge here is the rapid development cycle of ICT and power electronic devices: the behavior of the individual subsystems as well as their interaction with each other will change quickly over time, whereas it is also manifest to carefully address the integral system behavior over the assets' life span in planning studies performed today. It is therefore significant to set out scenarios, testing schemes, and sophisticated simulation platforms to take up this challenge [3].

The present behaviour of the power system still relies to a large extent on physical quantities such as the electromechanical and electromagnetic interactions of rotating machines, lines, converters, smart meters, etc. Studying behavior is generally speaking conducted on offline workstations in the time-domain by simulation experiments, and thereby using continuous modeling of components. Large systems that need to be simulated in high detail do usually not fit well into this approach. This gives rise to splitting the overall model into parts that are individually considered on separate processes that operate in parallel. Such *distributed models* are common practice for (real-time) electromagnetic transients (EMT) simulation.

Modern power systems contain also subsystems of very different nature for which continuous simulators are unsuitable. Computer networks and communication structures that fulfill dedicated control purposes have a discrete, event-driven nature, and show stochastically distributed latencies. As a matter of fact, some of these controls rely on automatic functionality based on heuristics, regulation (e.g., electricity markets, grid code compliance), or combined with human supervision. Such *multi-domain* systems do not fit very well into the current (monolithic) power system and components simulation paradigms.

The algorithms of single domain simulators have usually been developed and numerically optimized over decades, and extending such solvers to multi-domain functionality commonly compromises on the numerical behaviour (solver speed, accuracy), as discussed in part I of this article. It is therefore time to move towards simulation platforms that can handle multi-domain systems with reasonable detail and simulation speed. Coupled simulations or co-simulations aim to fulfill these needs by modeling multi-domain systems across multiple simulation tools, while acting as one integral simulation platform that addresses the study [4].

Until present, co-simulation (sometimes also referred to as combined simulation or co-operative simulation) in the power system domain has been mainly reported for single domain, distributed-model problems. Among these are real-time EMT simulation of smart grids [5], hybrid (SPICE-type) circuit–EMT–stability simulations [6], and parallelised EMT simulations on workstations [7], [8]. These approaches, however, did not implement the overall system as distributed models into separate simulation processes. In [5], for instance, a smart grid test setup was simulated in real-time. This is a multi-domain system under test being solved inside a particular fixed model framework, i.e., an electrotechnical (monolithic) continuous simulation. Pure co-simulation separates the models and the various solvers, and focuses on the coupling between the processes. Particularly for smart grids such a distributed approach would be of great advantage as distributed systems of arbitrary nature are interconnected via ICT or physical links.

Above considerations for co-simulation require the integration of simulation tools for intelligent electrical power systems beyond the state-of-the-art. No fully fledged alternative assessment method is available: experiments are expensive, time consuming, and are often restricted by the laboratory facilities. Especially for intelligent electrical trans-disciplinary power systems this is challenging. Monolithic multi-domain simulators on their turn allow assessing such systems at the cost of system scalability and sub-optimal numerical algorithms [9]. This gives rise to various challenges for co-simulations such as:

- Refined simulation and system testing and validation procedures (e.g., success parameters);
- Hardware-in-the-loop treatment (e.g., controller and amplifier interface standardization, harmonized data structures, master algorithm compatibility);
- Dedicated coupling and model library development (e.g., harmonization of models);
- Fostering applicability by standardization of interfacing techniques among the various tools involved; and
- Model and simulation coupling algorithms (i.e., numerical algorithms).

These challenges signify the need for a clear positioning of various aspects and implications of co-simulation in terms of power system assessment. The second part of the article on simulation of intelligent power systems covers the application of co-simulation to test cases that span various domains. This paper thereby mainly confines itself to systems that represent a hardware infrastructure, such as ICT and power engineering systems. Stochastic systems, big-data issues, and rule-based actors, which add an entirely different meta-level dimension to the heterogeneity challenge [10], [11], are outside the application scope of the paper. Figure 1 shows for instance a system under test inside the distribution system. It consists of a photo-voltaic plant grid-connected to the distribution network by a three-phase inverter. In a smart grid the control system is typically part of a larger, centralized control entity that provides high-level quantities such as voltage and power setpoint through telecommunication. For ensuring the interoperability of the PV plant at the coupling point, a series of experiments need to be undergone. Defining the actual test setup for assessing these test criteria is a challenge. Non-virtual (hardware) experiments, e.g., testing the PV plant in a laboratory, would impel the control part of the system under test to be significantly reduced or disregarded at all. Virtual (software) experiments, on the other hand, need an extensive model library of physical and discrete components, which need to be solved in a monolithic fashion. Co-simulations allow virtual and non-virtual experiments to be combined by interfacing refined domain-specific tools, or even go one step further and attach real controllers or power hardware-in-the-loop. Figure 1 shows how a typical co-simulation test setup can be achieved to accurately handle the higher-level controls for this particular test case.

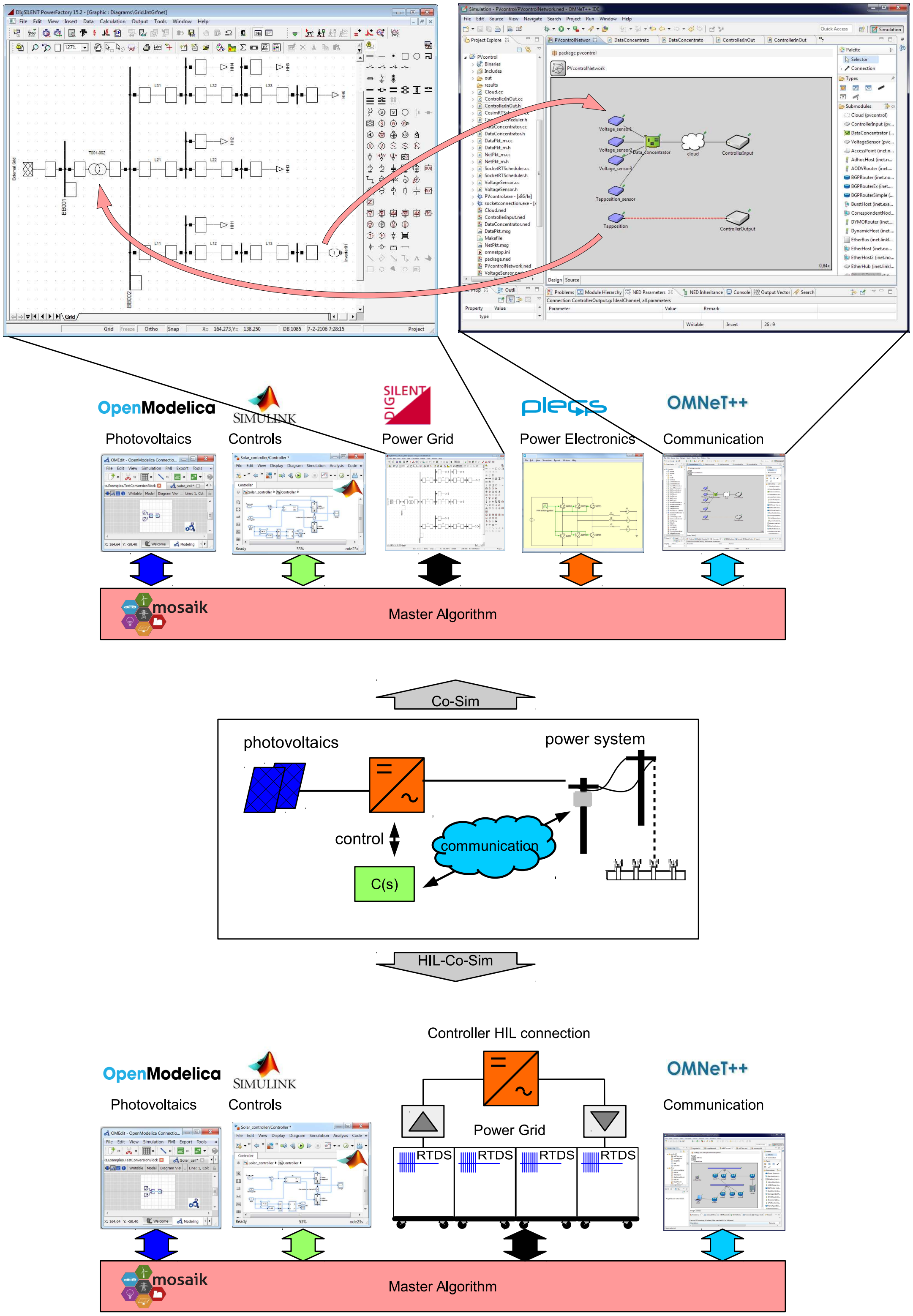

Fig. 1: Use case with a PV plant, an inverter with communicating controller, and a distribution grid (middle), that can be analyzed in a full co-sim fashion (upper setup) or in real-time with the real inverter in the loop (lower setup).

The remainder of this paper covers the application of co-simulation for the following typical setups: the connection between ICT and power systems (multi-domain heterogeneity), hardware-in-the-loop simulations (virtual + non-virtual experiments), and the combination of transient stability with an electromagnetic wave transients simulation (sub-domain heterogeneity). The paper ends with a survey of current challenges on the road.

II. ICT and Power Systems

ICT is playing an ever more prominent role in power systems. Developments like the *internet of things*, smart homes, or car-to-X communication further contribute to a data-driven power system. The use of ICT in power systems has diverse purposes, and just as diverse are the requirements it needs to fulfill. For example, timing constraints in communication range from very relaxed in the case of meter reading to very strict in the case of high-speed signals for protection purposes. The use of co-simulation to investigate the mutual impact of ICT and power systems, and therefore, the behavior of intelligent power systems, has become significant.

Noteworthy applications of co-simulation related to intelligent power systems are the analysis of wide area monitoring and control [12], control and optimization in distribution networks [13], [14], and distributed energy integration [15], [16]. In such applications, co-simulation can conveniently scrutinize interactions between systems of completely different natures. For instance, the impact of communication latency on the power system has been analyzed in [17], while the impact of cyber attacks on the electric power grid has been studied in [18], [19]. Co-simulation has also proven to be useful to explore artificial intelligence applications in power grids [20]. There is also extensive work on combining (classical and factory) automation standards with power systems [21], which increases the need for this type of co-simulations. Real-time/hardware-in-the-loop (HIL) test beds have been proposed for automation-related co-simulations [22], but it is expected that non-real time versions provide further insight into these systems. Setups like in [23] are currently used for evaluating the impact of latency or packet loss on smart grid control applications.

Over the past decade, profound efforts have been made to couple continuous power system simulators with discrete communication network simulators. The electric power and communication synchronizing simulator (EPOCHS) [24] is one of the first, and it combines power system simulators with instances of network simulator 2 (ns-2) at run time. The global event-driven co-simulation framework (GECO) [25] for evaluation of wide area monitoring and control schemes integrates PSLF with ns-2. GECO runs globally in a discrete event-driven manner whereas a global event scheduler is used to handle power system iteration events and communication network events. The integrated co-simulation of power and ICT systems for real-time evaluation (INSPIRE) [26] uses the High Level Architecture (HLA, IEEE 1516) for time management, providing a co-simulation platform for modeling the effects of ICT infrastructures on power grids. Table I provides a non-exhaustive list of examples of co-simulation of power systems and ICT infrastructure.

A notable feature of co-simulations of intelligent power networks is the different time scales that are combined in one model. Figure 2 shows various applications and phenomena in various power system domains. Their characteristic time constants range from microseconds to minutes. The applications and phenomena that exhibit

Name	Application	Components	Synchronization	Time scale	Scalability
EPOCHS [24]	Protection and control schemes	PSCAD/EMTDC, PSLF, and NS-2	Synchronization points-based	From microseconds to minutes	Suitable for large systems
OpenDSS & OMNet++ [27]	Wide area monitoring and control	OpenDSS, OMNet++	Synchronization points-based	From milliseconds to minutes	Medium size
Adevs+NS-2 [28]	Wide area monitoring and control	Adevs, NS-2	Event-driven	Limited range	Suitable for large systems
GECO [25]	Wide area protection and control	PSLF, NS-2	Event-driven	From milliseconds to seconds	Suitable for large systems
Greenbench [18]	Cyber security in distribution grid	PSCAD, OMNet++	Event-driven	N/A	Tested in small systems
PowerNet [29]	Monitoring power grid devices	Modelica, NS-2	Master-slave	N/A	Unsuitable for large systems
VPNET [30]	Networked power converter system	VTB, OPNET	Master-slave	N/A	Unsuitable for large systems
INSPIRE [26]	Monitoring and control	DIgSILENT PowerFactory, OPNET	Master-slave	From microseconds to minutes	Suitable for large systems
OpenDSS & NS-2 [31]	Distributed energy resources integration	OpenDSS, NS-2	Not addressed	From milliseconds to seconds	Medium size
TASSCS [19]	Cyber security of SCADA	PowerWorld, OPNET	N/A	Real-time in communication network	Suitable for large systems

TABLE I: Examples of co-simulation of power systems and ICT infrastructure

small time constants would require smaller time steps for calculation in simulation [32]. Thus, the separate co-simulation entities of intelligent power grids should correctly represent their time characteristics.

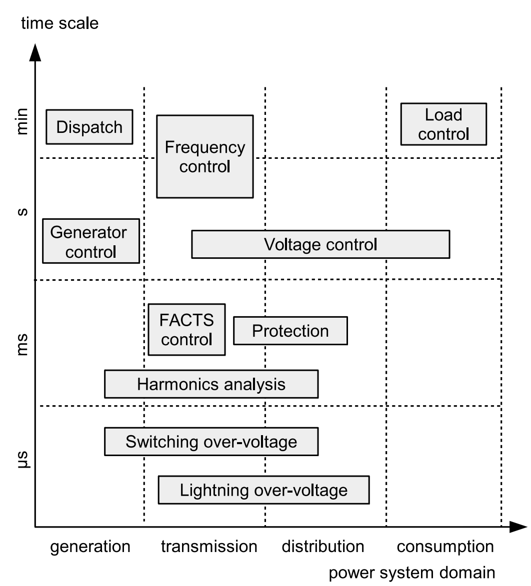

Fig. 2: Time scales of various power grid applications based on [32].

ICT, and especially the controls of intelligent power grids, expose another important aspect that the simulation models have to consider: real-time guarantees. As shown in Figure 3, some protocols offer real-time guarantees, while others operate on *best-effort* basis (i.e., no communication speed or fidelity is warranted by the respective protocols). The associated applications either rely on guaranteed latency and throughput or have a more relaxed use. Regardless of these bounds, the real-time guarantees might be needed at different time scales. An IEEE C37.118 for Phasor Measurement Unit (PMU) based monitoring system, for example, needs fast and guaranteed transport. IEC 61850, an Ethernet-based communication standard for substation automation systems, combines real-time and best effort services like generic object oriented substation event (i.e., GOOSE) and manufacturing message specification (i.e., MMS).

From the above, it is evident that the flexibility of co-simulation allows the consideration of mixed ICT and power components/systems for different time-scales, even in real time. As shown in Table I, there are examples of co-simulations that consider different time scales, according to their specific application. For phenomena that involves loose real-time guarantees and long time scales, e.g., Advanced Metering Infrastructure (AMI) reading, it would be possible to choose the interfacing and synchronization methods introduced in Part I. However, for phenomena that involves strict real-time guarantees and short time scales, e.g., PMU based monitoring, it is challenging to design capable interfaces and appropriate synchronization methods. Real time co-simulation techniques which are based on powerful real-time simulators are hence needed under such circumstances, as will be detailed in Section III.

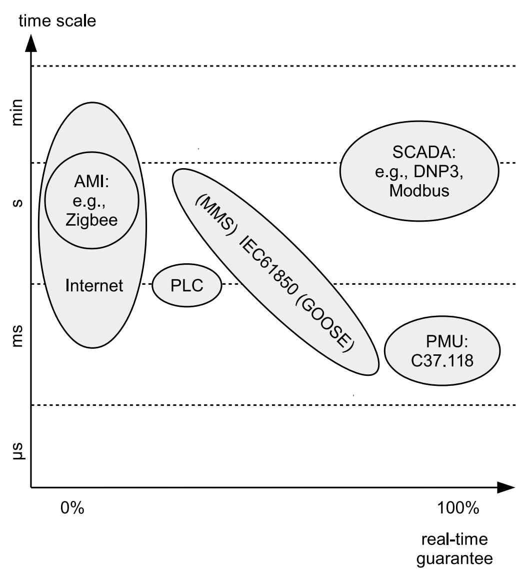

Fig. 3: Real time guarantees and time scales of power system communication protocols.

III. Real Time Simulation for Intelligent Power Systems

If the simulators compute model time as fast as a wall clock time, real-time simulation is possible. The main reason behind real-time simulation is the need to connect real equipment that interacts in real-time with the simulation. For this to be possible, the simulator needs to solve the model equations representing the actual power system network, power electronic device, or communication system for one time-step within the same time as in a real world clock. Real-time simulation applied to the domain of intelligent power systems can be classified in two categories: fully digital and hardware-in-the-loop real-time simulations. In fully digital real time simulations, the entire model of the system under analysis is simulated on a dedicated platform with simulation software that can ensure the fulfillment of real-time constraints. In HIL simulations, a part of the model is replaced by an actual physical component (e.g., a controller, power electronic device, etc.). Thus, for HIL simulation, a digital real-time simulator (DRTS) with interfacing capabilities for connecting external devices required.

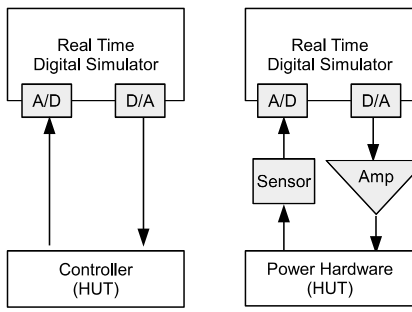

Fig. 4: Basic structure of CHIL and PHIL simulation.

HIL simulation can be classified in two types: Controller HIL Simulation (CHIL) and Power HIL Simulation (PHIL). Figure 4 shows the basic implementation structure of both CHIL and PHIL simulation.

In CHIL simulation, the controller, or hardware under test (HUT), is connected to the simulated system directly through the interface of the DRTS using low power signals. The interface can be realized through the analog to digital converters (ADCs) and digital to analog converters (DACs) of the DRTS, or even with other communication protocols such as sockets in the case of HUTs that support such methods. CHIL is used for testing controllers in early stages of design for power electronics devices like inverters, flexible AC transmission System (FACTS) and high voltage DC (HVDC) systems .

In PHIL simulation, actual power transfer takes place to and from the HUT, which makes it more complex and risky [33]. As shown in Figure 4, the main components of a PHIL simulation include a power system simulated in a DRTS, an amplifier, sensor and HUT. The amplifier provides the operating power to the HUT based on the low-power input signals from the DRTS, while operating conditions of the HUT are sensed and scaled to power levels compatible with the DRTS, and then fed back to the DRTS. A part of the power system is internally simulated and another part is a real hardware power apparatus. Thus a power source or a sink (connected through the PHIL interface) is required to generate or absorb the power needed. The main components of a PHIL simulation are the following:

- *Digital real-time simulator (DRTS):* Industrial grade simulators like RTDS or OPAL-RT are the most commonly used DRTS for power systems. They are dedicated systems with hardware supporting all the interfacing and ensuring real time simulation of very large systems with small simulation time steps in the order of micro seconds. Table II summarizes the features of different real time simulators used for power engineering applications in terms of interfacing methods used, type of hardware used, communication protocols supported, solver and simulation software used, etc., according to [34]. The main advantage of such DRTS systems is that they have libraries with application-specific models that are accepted by the industry.

- *Power amplification unit:* A power amplifier allows the transfer of power between the HUT and the part of the power system simulated in the DRTS at the point of common coupling. The selection of such an amplifier plays a crucial role in the stability and accuracy of PHIL simulation, since these factors are influenced by parameters like bandwidth, slew-rate and short circuit behavior. [35]. .
- *Interface algorithms:* Interface algorithms provide the means for relating the voltages and currents on the DRTS side to the HUT side of the PHIL simulation. They play a critical role in determining accuracy and stability of a PHIL simulation. Figure 5 shows an example of an interface algorithm called *ideal transformer method.* In this figure, Z_1 and u_0 represent the DRTS, and Z_2 represents the HUT. The voltage and current at the point of common coupling are replicated as closely as possible using voltage and current sources. The ideal transformer method is the most commonly used interface algorithm due to ease of implementation, but its stability depends on the source to load impedance ratio. Alternative algorithms are reported in [33], [35], [36].

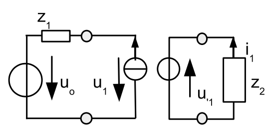

Fig. 5: Ideal transformer method for interfacing power hardware and a real time digital simulator.

A. HIL Simulation of Intelligent Power Systems

The applications of HIL simulation in the field of power engineering include the testing of protection devices, HVDC systems, and FACTS . HIL is also employed for distribution system studies such as integration of distributed energy resources . HIL simulation serves as a tool in the rapid development and testing cycle for the integration of ICT and intelligent electronic devices into intelligent power systems. Among the noteworthy applications are the following:

- *Relay testing:* This is one of the most popular and oldest applications of HIL simulation , and is presently used for design, study and testing of relay coordination, and distance relay protection [37].
- *Testbed for control strategies:* With the availability of different communication protocols, like TCP/IP and standards like IEC 61850, C37.118, PMU, and DNP3 incorporated in the DRTS system, it is possible to develop real time testbeds to design and implement control strategies for large power systems and power electronic components setups to study their impact on the system configuration. Examples of such applications are SCADA test beds for applications like energy management schemes and simulation of cyber attacks [38], passive islanding studies based on PMU data [39], testing of power control of wind parks with energy storage [40], testbeds for control design of microgrid energy management systems [41], and design and validation of wide area control systems [42].

Real Time Simulator	Hardware	Interfacing and I/O	Communication Protocols	Solver Type	Software Supported
RTDS from RTDS Technologies Inc.	Proprietary boards with PowerPC RISC processors and FPGAs	optical fiber, fast back plane, global bus hub, Gigabit Ethernet, analog and digital I/O, third party I/O through GTNET	IEC61850, TCP/IP, C37.118, PMU, DNP3	Dommel's algorithm based nodal solver	RSCAD
eMegasim from OPAL-RT Technologies Inc.	Multicore CPU, FPGA, commercial-of-the-shelf motherboard	shared memory, Gigabit Ethernet, Dolphin networking, FPGA based analog & digital I/O terminals, supports third party I/Os	IEC61850, C37.118, DNP3	ARTEMIS-SSN, discrete Simulink Solvers	Simulink, C/C++, Matlab, Fortran wrapped in S-function
HYPERSIM from OPAL-RT Technologies Inc.	SGI Super-computer with SGI and Intel CPUs	Gigabit Ethernet, Standard PCIe interface with DSP based ADCs and DACs	IEC61850	state space solution method is used with multiple integration rules	Hypersim Software Suite
Typhoon HIL from Typhoon HIL Inc.	Proprietary ASIC	FPGA based analog and digital I/Os	IEEE 1284C, Ethernet RJ45	Typhoon schematic editor, SpiceShuttle, Matlab	Typhoon Software Suite

TABLE II: Summary of features of real time simulators for power systems.

- *Design, testing and validation of power electronic devices:* With the availability of high performance I/O terminals of resolution close to 10 ns, a DRTS can be used for testing a wide variety of power electronic devices, ranging from inverters, FACTS, and HVDC devices, to the latest intelligent electronic devices. Some recent applications include testing of power electronic controllers [43], STATCOM controller validation for wind park applications [44], PHIL testbeds to analyze the impact of plug-in hybrid electric vehicles on the grid [45], PHIL testbeds for HVDC systems [46], and PHIL testbeds for grid integration analysis of PV inverters [47].

B. Real-Time Co-Simulation of Intelligent Power Systems

Many multi-domain [48] and multi-physics [49] applications of HIL simulation integrated with co-simulation can be found in the literature for diverse fields of engineering. In [48], a multi-domain co-simulation procedure with HIL capability is proposed for the design and analysis of electric propulsion systems. A concept of multi-physics PHIL testbed as shown in Figure 7 is developed for the testing of renewable energy systems, and is applied to domestic energy systems [49].

Considering the the state-of-the-art of computing, sensing, and communication technologies, it is reasonable to assume HIL integrated with co-simulation capabilities will become a relevant tool for the study and analysis of future intelligent power systems. Applications of such HIL co-simulation testbeds include analyzing distribution grids for demand response strategies [50], and testing of demand side management techniques to provide ancillary services [51]. In [50] the VirGIL HIL co-simulation testbed is introduced using a master algorithm developed in Ptolemy II that coordinates the data exchange between all individual components. The communication between different components is done using the FMI standard. The individual components include PowerFactory as the power system simulator, OMNeT++ for the communications network simulator, Modelica for the building model/control, and the Ptolemy II environment for HIL simulation. The real-time PHIL co-simulation testbed introduced in [51] consist of a demand side management module, real-time simulator module (by Applied Dynamics International) and micro-grid module. A HIL co-simulation testbed is developed in [52] using the HLA framework and the IEEE 1516 HLA standard. Figure 6 shows the proposed architecture with a run-time infrastructure (RTI) and three individual federates, a network simulator federate, a Power-Sim federate and a HIL federate, facilitating the co-simulation environment. The power system simulator is connected to the Power-Sim Federate via a OLE for Process Control Data Access (OPC DA) server connection and a virtualized execution platform is used for the execution of the control application. The HIL interface is responsible for the synchronization of data exchange between the co-simulation and the virtualized execution platform. A PHIL platform with remote distribution circuit co-simulation is described in [53], where the real time coupling between the PHIL simulation and distribution system simulated in GridLAB-D is facilitated using a JavaScript Object Notation (JSON) based data exchange protocol.

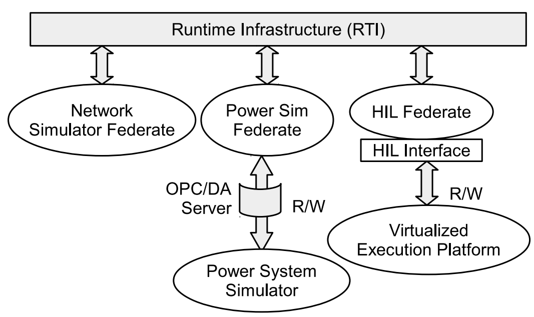

Fig. 6: Hardware in the Loop Co-Simulation Architecture [52].

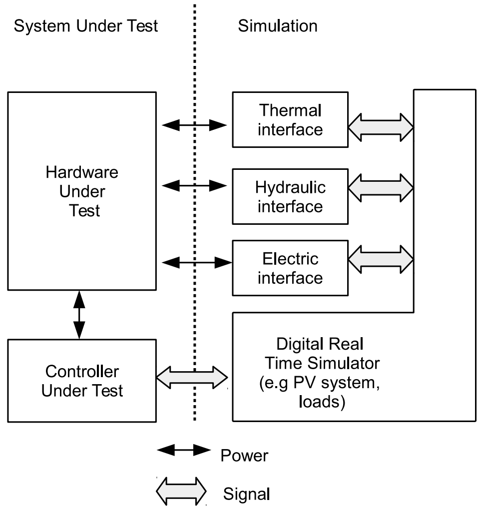

Fig. 7: Concept of multiphysics PHIL platform based on [49].

Real-time co-simulation also serves as a platform to study the mutual impact of coupling power systems and ICT infrastructure in an intelligent power system framework. One of the major application of such a platform is the study and analysis of methodologies for controlling and monitoring large power systems with PMU based WAMPAC systems. Some of the efforts to build such a real-time co-simulation platform are:

- *RTDS based:* In [54], RTDS is used for power system simulation and the ns-3 network simulator is used to simulate the communication system. This testbed is mainly for wide area monitoring protection and control research. In [55], RTDS and the OPNET network simulator are coupled. The communication card and the system-in-the-loop simulation feature of OPNET are used for data exchange with the help of NI PXI as the interface. A real-time co-simulation test bed is developed in [56] for analyzing the impact of cyber events on microgrids using RTDS as power system simulator and common open research emulator (CORE) as communication network emulator. It should be noted that developing large power grid models based on RTDS is rather expensive since the hardware requirements scale linearly with the number of simulated nodes.
- *OPAL-RT based:* OPAL-RT is another platform that supports real-time (co-)simulation. The Orchestra API acts as the co-simulation scheduler and coordinates the components connected to OPAL-RT. In [57], this co-simulation environment makes use of the compatibility of OPAL-RT and Simulink to develop PMU applications. The system-in-the-loop of OPNET and SoftPMU is used for interfacing and data exchange. In [5], a comprehensive micro-grid co-simulation with OPAL-RT and OPNET is built. It can achieve real-time simulation with hundreds of switches at a high switching frequency (up to 10 kHz).
- *PowerFactory based:* DIgSILENT PowerFactory, a versatile power system simulator for workstations, also provides a real-time mode. PowerFactory can be interfaced with other hardware/software components through the OPC communication protocol and various APIs. In [58], the PowerCyber testbed is built using the integration of PowerFactory with intelligent electronic devices and remote terminal units in order to perform cyber-physical security testing.

IV. Use Case on Interfacing Stability-type with EMT-type Simulations

A. HVDC and Power System Electrotechnical Simulations

For pure electrotechnical simulations it is common practice to consider only the phenomena of interest for the dynamic power system model. For decades, the response of interest was mainly related to the size of the system under study or the event being invoked. Using this approach, grid integration aspects of devices and systems could be studied separately and deterministically. Rotor angle stability for instance was a system-wide aspect mainly triggered by short circuits. Hence, studies could be conducted by simplified quasi-stationary models. Over-voltages, startup and inrush behaviour, and harmonics were as a rule caused by local devices and (passive) network components. This allowed a considerable network reductions for the electromagnetic transients simulation. The main simulation tools were hence transient stability-type simulations and EMT-type simulations.

The introduction of power-electronic interfaced devices and transmission systems put these paradigms into a different perspective. Especially line-commutated high voltage DC transmission did not fit well into the classical simulation approach as the detailed power electronic responses could have significant influence on system-level quantities such as voltage and rotor angle stability [59]. Several interim solutions were developed to maintain the concept of two separate simulation approaches. Examples include static modeling of HVDC links [60], and generic dynamic modeling, for EMT [61] and stability-type simulations [62] alike.

In the 1980's a widely accepted approach to include detailed HVDC converter behavior into stability-type simulations was published [63]. In this paper, the transient stability-type simulation acted as the master simulation and engaged a quasi-stationary model of the HVDC link under normal operating conditions. During disturbances, however, this model was replaced by an EMT-type model that interfaced with the master simulation. The interfacing techniques employed acted as the starting point for numerous future improvements of this concept, such as 1) generalisations on the EMT network segment type [64], [65], 2) generalisation on numerical implementations such as event handling [66], 3) interaction protocols [67], 4) parallelisation [68], 5) accuracy improvements [69], 6) dedicated interfacing techniques for VSC-HVDC links [70], [71], 7) advanced treatment of sequence components [72], and 8) refined decomposition methods for assessing the transient stability problem [73].

B. Interfacing TS and EMT Simulations

In terms of the taxonomoy of part 1 of this paper, interfaced EMT and stability-type simulations can be categorized as co-simulation, i.e., having multiple models and multiple solvers. Although the system itself is entirely modeled in the physical domain, it is split up into two types of models: an *external* subsystem being solved by the stability type simulation, and a *detailed* subsystem that is studied using an EMT-type simulation. Each subsystem has a different type of solver. The stability-type simulation can for instance apply a wide variety of solution methods for solving the set of DAEs (e.g., implicit versus explicit solvers, partitioned versus simultaneous solution methods). For EMT-type simulations on the other hand there is one mainstream method, the nodal analysis method, where the entire system of differential equations is discretized and mapped to the trapezoidal rule of integration. Notwithstanding the categorization into a multi-domain, multi-solver type of simulation, power system electrotechnical co-simulations are commonly referred to as hybrid simulations, mainly for legacy reasons. To prevent inconsistencies we abide by the term co-simulation.

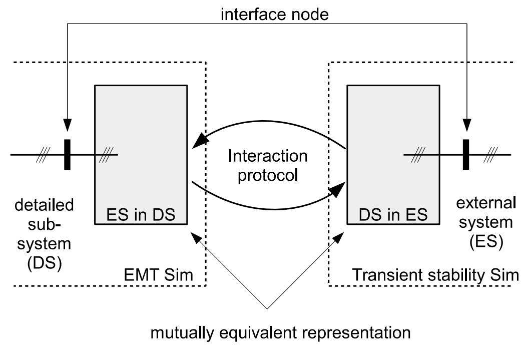

Fig. 8: Detailed and external subsystem coupling for EMT–TS co-simulations.

Stability-type and EMT-type co-simulations predominantly apply the coupling arrangement shown in Figure 8, comprising the following:

- The detailed and external subsystems included into the EMT-type and stability-type simulation respectively;
- The coupling location (i.e., *interface node*) and/or network segment; and
- The representation of the subsystems into each other by means of equivalent sources;
- The *interaction protocol* that handles the communication sequences between the solvers.

The coupling location is commonly an AC node but mutual network segments have also been studied [74]. The former provides modeling simplicity whereas the latter bears potential accuracy advantages. The coupling location determines to a large extent the accuracy of the combined solution: the larger the detailed subsystem, the higher the level of detail can be achieved (e.g., unbalanced conditions, harmonic distortion). This however also increases the computational burden, which is one of the main benefits of TS and EMT co-simulations.

In order to facilitate interfacing information about flow and effort between the subsystems, either needs to be represented into the other. As a rule this is done by dynamic Norton or Thévenin equivalents, which during the communication step (see part 1 of this article) dictate a voltage source or current injection based on the system quantities available at t_k. For the representation of the detailed subsystem into the external subsystem this is generally speaking the transformation of point on wave currents and voltages to positive sequence quasi-stationary phasors. For the inclusion of the external subsystem dynamics into the detailed subsystem on the other hand this involves the transformation of positive sequence phasors to symmetrical voltage or current sources. Depending on the level of emphasis of the study and the modeling detail required the impedance of the equivalent source representation inside the detailed subsystem can be mapped at fundamental frequency, or can be implemented using a wide-band equivalent [75]. The latter is employed in case an accurate representation of the external subsystem is needed over a wide range of frequencies and the determination of these is far from trivial and commonly involves coherency determination [76], among others [77].

A common way of implementing a power system electrotechnical co-simulation is to set the stability-type simulation as the master orchestrator, and thereby embedding the EMT-type simulation into this main simulation by an inner calculation loop. This algorithm is shown in Figure 9 and implemented in [70]. At t_0 the overall simulation starts with an AC/DC power flow and thereby initialising the network, device, and interface models for both the external and the detailed subsystem [78]. As the stability-type simulation acts as the master, interfacing is carried out each (fixed) macro time step of the simulation, i.e. $h = \Delta t$ and $t_k = t_n$. This output exchange towards the detailed subsystem typically entails the following steps:

1) Fetch interface nodal quantities from the external subsystem;
2) Make these effort and flow variables compatible with the detailed system modeling approach (compare with the communication sequences explained in part 1 of the article);
3) Apply interpolation or extrapolation inside the detailed subsystems, depending on causality conditions.

Subsequently, the detailed subsystem executes its minor time steps until reaching the condition $t_{\text{emt}} = t_{n+1}$. Now the detailed system has to send its output to the external subsystem, akin to the steps taken while interfacing between the external and detailed subsystems. What follows is that the stability-type simulation continues solving the subsystem's set of DAEs until reaching $t = t_{n+1}$, at which the master (TS) simulation advances the overall time step. The above-mentioned sequence follows the serial (Gauss-Seidel) communication sequence and makes up a weakly coupled simulation. A similar calculation sequence is applied in commercially available simulation packages like PSS®NETOMAC [79]. Fully separated simulation environments are reported in [80] (Powerfactory with MATLAB/Simulink) and in [72] (InterPSS with PSCAD/EMTDC). In general the challenge is to make the synchronization algorithm compatible with the simulator properties. When the master or one of the simulation federates does for instance not support rolling back in time, using adaptive time step sizes, or model-specific mockup services like derivative determination, the capabilities of the co-simulation as a whole are inhibited.

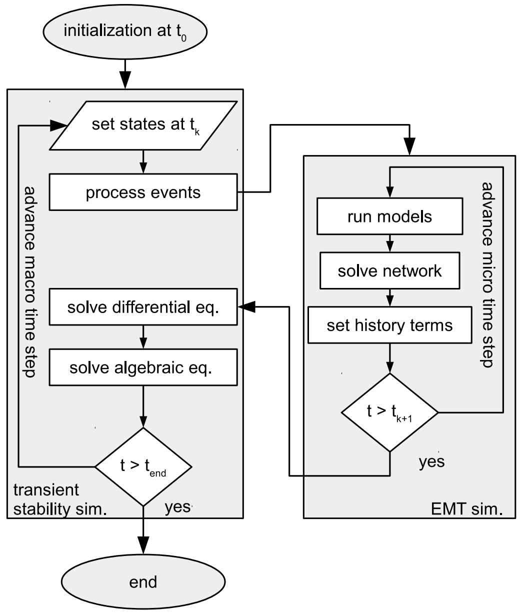

Fig. 9: Workflow of an electrotechnical EMT–TS co-simulation, in which the transient stability simulation acts as the master simulator.

C. Co-Simulation Implementation for VSC-HVDC

The next generation of HVDC transmission based on voltage sourced converter technology (VSC-HVDC) has the potential to transmit power in the GW range. Despite the superior controllability of such interconnections, the AC/DC interactions cannot be safely disregarded in grid integration studies, particularly during fault-ride through conditions [81]. This gives rise to co-simulation applications. This section gives an survey of the functionality requirements of the co-simulation environment.

From an operation viewpoint VSC-HVDC links can be mainly separated into 3 types: offshore wind power plant connections, VSC-HVDC links embedded in one synchronous area, and multi-terminal schemes. The control design of point-to-point links primarily focuses on 1) conveying the active power infeed towards the opposite VSC terminal, 2) device and HVDC primary equipment protection, and 3) ancillary services. Active power set points are typically set by either the system operator or imposed by the wind power plant output. Fault-ride through of point-to-point links is commonly achieved using overvoltage protection devices inside the DC link (i.e., dynamic breaking resistors), whereas fault interruption is done via the AC side. Strictly speaking, point-to-point VSC-HVDC schemes do not need any (fast) communication that might suddenly inflict unexpected behavior at the AC-side. Multi-terminal schemes do not comply very well to this concept as DC faults should be cleared selectively, the direction of active power flow shall be controllable, and sophisticated fault-ride through and/or ancillary services must be engaged.

This operational functionality also puts a burden on the simulation and modeling needs. fault-ride through might engage lower level (component-specific) protection mechanisms such as converter module blocking, which on their turn inflict severe perturbations in the power output. Such events necessitate the inclusion of a wide spectrum of physical phenomena into the overall (physical) system assessment. Another notable domain of interest is the (fast) communication needs of VSC-HVDC links. The inclusion of ICT-specific models into the overall system assessment is more effective using a dedicated domain-specific model and corresponding solution algorithm.

The relatively fast inner control loops of VSCs needed refinement of conventional interfacing techniques mainly on the following aspects:

- Equivalent source representation inside the detailed subsystem: it needs to represent the characteristics of the external system, at least for power frequency but preferably also for higher harmonics [76]
- The extrapolation procedures for the external system quantities into the detailed subsystem: voltage angles and magnitudes are synchronized as algebraic variables, which allows discontinuous jumps at synchonization instants. Extrapolation estimates the trace of these quantities leading to a more realistic VSC-HVDC model response.
- Improving causality conditions for the extrapolation steps: specially at faults no historical information is available for extrapolation or interpolation of the synchronized variables. Temporary interaction protocol adjustments can partly address the related model response issues. and
- Phasor capturing methods for small time step-size conditions: notably during small or adaptive time step-size conditions the discrete Fourier transform need values from the detailed system also from previous synchronization points, e.g., t_{k-1}, t_{k-2}; the interaction protocol has to cater for this.

As part of the focus of grid integration studies is on the compatibility with the AC transmission system behavior, the largest part of the co-simulation is contained within the external subsystem. As a matter of fact, the events under study are generally speaking AC side faults causing voltage dips at the point of common coupling. Interface technique improvements hence focus on optimizing the behavior during events inside the external subsystem.

Figure 10 shows an interaction protocol that changes the calculation sequence during events and was proposed in [70]. The figure shows two time lines that represent the minor steps of each subsystem. The detailed subsystem, which is shown on the bottom, employs a fixed time step-size of Δt_{emt}. For the sake of simplicity Δt_{emt} fits exactly M times in the time step-size of the master simulation. The arrows with encircled numbers indicate the simulation and interfacing actions conducted by the co-simulation. The normal calculation sequence is to first run the external subsystem and thereby enabling advantageous causality conditions for the detailed subsystem's source magnitude and angular interpolation. Then provide output to the detailed subsystem, run it, and interface the obtained phasors back to the external subsystem.

We assume an event at t_n, inducing a solution of the algebraic equations as the system of DAEs changes ①. The normal sequence is now inconvenient as source values cannot be interpolated, nor extrapolated. Therefore, the calculation sequence is adapted to first prioritize the detailed subsystem (i.e., ② and ③) using zero-order hold values of source quantities obtained at ①, and hence providing its response undelayed to the external subsystem ④. Then the simulation advances towards t_{n+1} (i.e., ⑤) while using the same phasor quantities as the previous output exchange (i.e., ⑥). Next, the interaction protocol returns to its default calculation sequence (i.e., ⑦ - ⑨). This interaction protocol 1) enables accurate response right after faults, 2) enables causal interpolative filtering, and 3) shows favorable accuracy characteristics against a full EMT reference simulation.

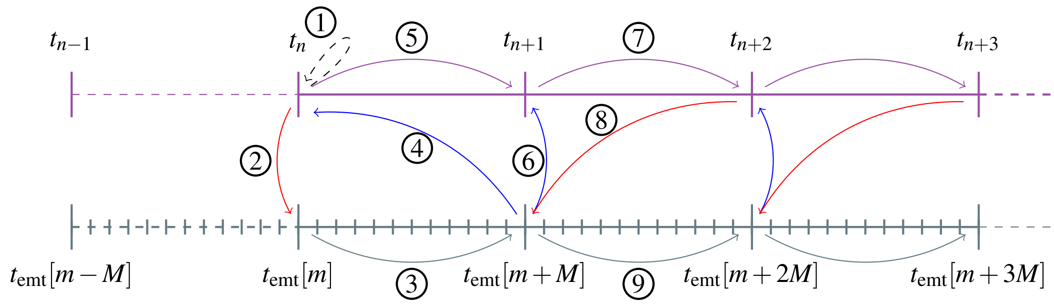

Fig. 10: Interaction protocol change in the event of faults inside the external system.

V. Conclusion and Outlook

This paper gives the latest developments in co-simulation of intelligent power systems. The aspects of discrete and continuous models, of hardware in the loop simulations, and of applying co-simulation in a complex power system setting are covered.

Co-simulation has several advantages when working with intelligent power systems: proven tools with validated models can be used, virtually every style of heterogeneity (e.g., multi-rate, or power-to-gas-to-heat) can be dealt with, and the system model has by design a modular structure.

There is, however, still no established standard or platform to couple domain-specific simulators in order to create a smart grid simulation platform. Table III shows a non-exhaustive list of properties of three popular smart grid co-simulation federates. Their features and interfaces are far from being harmonized, which is the typical situation when a set of tools is expected to form a joint, hybrid simulator. The integration task therefore not only consist of writing drivers or interface wrappers but also semantic efforts (e.g., represent events in a non-event simulator, interpolate or extrapolate between time steps, etc.).

Most incompatibilities that are worked around lead to performance problems. But even if the interface is frictionless, the models themselves are often challenging with respect to scalability and performance. One small and maybe even unimportant part of the system model can grind everything down if its step size is small and strict synchronization is enforced. Such cases can only be solved with carefully developed model where the designer is well aware of the time constants, events, and dependencies.

The most urgent topics that require research are

- Languages: Is there hope for a unified modeling language for all the aspects, ranging from electromagnetic transients up to market mechanisms? Do languages like Modelica move into the right direction? Currently these languages are lacking validated models for the power domain that can compete with existing, commercial simulation products. Also the scalability of the associated software packages is not suitable for simulating large systems[82]
- Documentation: How can models be documented, so that revisions, details, and collaborative work can happen over a long time? This is a topic well known in software and collaborative development. Currently there is no established method of documenting and tracing complex projects like power system co-simulation that can

easily be deployed.

- Formats: Which standards are the most promising for time series, parameters, libraries or components [83]? Emerging standards like hdf5 (hierarchical data format) and XML-based industry standards should be sufficient for these needs. Many tools, however, still use comma-separated value lists and other non-descriptive formats.
- Distributed computing: How can we split large systems into parts to run them on a distributed computing environment? Platforms like HLA are prepared for distributed computing. The key point, however, is performance, which in turn boils down to how the used hardware and the compilers/software are balanced against each other. Most known parallel attempts use nodes connected via general-purpose communication networks, which is far away from real parallel computation.
- Multi-granular models: How can we define models with different levels of details to perform a coarse analysis on the simple ones and to dive into the details once something interesting is discovered. What role can object-oriented modeling languages play in this question? Models in Modelica could incorporate different version of the component behavior, e.g., a static, a linearized and a detailed. Depending on the simulation run, one of them can be activated. This could help to quickly chart the search space and later investigate the interesting areas.
- Complexity: System complexity rises dramatically if a formerly continuous system is enhanced with digital elements that show memory (digital controllers and software in general do that). The number of system states explodes and validating system behavior becomes a difficult task. Is an exhaustive search needed when varying parameters or are smart optimization algorithms capable of exploiting the peculiarities of intelligent power grid models? Modern hybrid metaheuristics are much more efficient in searching complex spaces. It is an active field of research where we still expect substantial progress [84].
- Heterogeneous models: How can we combine statistical models, topological models, physical models, and all the other ways that provide valuable information of our intelligent power systems? If aspects are optimized in one model domain, how can we harmonize that with the others? The need for multiple languages in describing systems led to the development of the unified modeling language UML. While it has gained substantial acceptance in other domains, it did unfortunately not receive much resonance in the power domain except its use in InterPSS, CIM (Common Information Model, based on UML), and some academic projects.
- Numerics: How do uncertainties in input data or model data propagate through co-simulation? Do individual model inaccuracies and solver errors add up or multiply when combined? This is a highly complicated topic. How errors propagate and how uncertainties live on in a complex simulation is an active field of research [85].
- Validation: How to validate results when a monolithic simulation is not longer possible and therefore no benchmark exists? Model validation is expensive if it is done via real experiments. The classical workaround is to validate against another established and accepted model or tool. Co-simulation can simulate systems that are too large for monolithic, validated tools, which therefore can not serve as a validation benchmark [86]. The only workaround available for this dilemma is to use a mix of experiments and different flavors of co-simulation to validate the simulators against each other [87].

	PowerFactory	OpenModelica	OMNeT++
Domain	power system (power flow, transient stability, EMT)	multi-domain,multi-physics	communication, ICT, agents
License	commercial	open source (GPL derivative)	open source (GPL derivative)
FMI model exchange	n/a	import and export	
FMI co-simulation	power flow only	only master simulator capable	
RT capability	RT flag	n/a	native
model/project data format	binary	XML, text	text
API co-simulation compatability	OPC, Python	FMI	C++
Access to time stepping	Via API	Via FMI	Reprogram scheduler
Community size/support, forum	professional support	active open source community, forum	forum

TABLE III: Comparison of (co-)simulation specific parameters of three popular tools.

Co-simulation is the method of choice if power systems are heterogeneous and/or large. Its ability to combine sub-models of entirely different nature makes this method attractive for cases such as power-to-heat, electric mobility, transmission/distribution interplay, or dynamic interactions between the power system and power markets. As always, the better the model, the better the results. Often, legacy and black-box simulators have to be integrated which can negatively influence performance and accuracy. On the other hand, new modeling languages such as Modelica enrich the capabilities of smart grid modelers. Innovative system components such as batteries or renewable sources can be described in a multi-physics manner and still be fully integrated in a power systems analysis. Still, the above challenges still require intensive work and research in order to fully exploit the idea and benefits of co-simulation for intelligent power systems.

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