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DOI
10.1109/MIE.2017.2671198

Publication date
2017

Document Version
Final published version

Published in
IEEE Industrial Electronics Magazine

Citation (APA)
Palensky, P., Van Der Meer, A. A., López, C. D., Joseph, A., & Pan, K. (2017). Applied Cosimulation of Intelligent Power Systems: Implementing Hybrid Simulators for Complex Power Systems. *IEEE Industrial Electronics Magazine*, *11*(2), 6-21. https://doi.org/10.1109/MIE.2017.2671198

Applied Cosimulation of Intelligent Power Systems

Implementing Hybrid Simulators for Complex Power Systems

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Smart grids link various types of energy technologies, such as power electronics, machines, grids, and markets, via communication technology, which leads to transdisciplinary, multidomain systems. Simulation packages for assessing the system integration of components typically cover only one subdomain, while greatly simplifying the others. Cosimulation overcomes this by coupling subdomain 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. The article "Cosimulation of Intelligent Power Systems: Fundamentals, Software Architecture, Numerics, and Coupling," published in the March 2017 issue of this magazine [88], covered the fundamental concepts of this topic, and this follow-up article covers the applied aspects of the subject.

Digital Object Identifier 10.1109/MIE.2017.2671198
Date of publication: 23 June 2017

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Simulating Smart Grids

Recent developments in information and communication technology (ICT) architectures, the massive installation of distributed energy resources, and the emergence of demand-side energy management instruments have led 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, as with energy storage options in gas or heat networks. The merits of the evolution toward intelligent electric power systems are evident: the higher controllability of the electric power system potentially improves its reliability and general operability, thereby benefiting the electricity market.

In planning studies performed today, it is necessary to carefully address the integrated system behavior over the assets' life span.

The operating service of power system assets commonly spans several decades. A specific challenge here is the rapidity of the development cycle of ICT and power electronic devices, because the behavior of the individual subsystems and their interaction with each other change quickly over time. Thus, in planning studies performed today, it is necessary to carefully address the integrated system behavior over the assets' life span. It is, therefore, important to set out scenarios, testing schemes, and sophisticated simulation platforms to meet this challenge [3].

The present behavior 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, and so forth. Generally speaking, this behavior is studied on offline workstations in the time domain through simulation experiments, thereby using continuous modeling of components. Large systems that need to be simulated in great detail do not usually fit well into this approach. This gives rise to splitting the overall model into parts that are individually considered in terms of separate processes that operate in parallel. Such distributed models are common practice for real-time electromagnetic transient (EMT) simulation.

Modern power systems also contain very different subsystems 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. Some of these controls rely on automatic functionality based on heuristics or regulation (e.g., electricity markets and grid code compliance) or on such functionality combined with human supervision. Such multidomain systems do not fit 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 multidomain functionality commonly compromises the numerical behavior (solver speed and accuracy), as discussed in part 1 of this series [88]. It is therefore time to move toward simulation platforms that can handle multidomain systems with reasonable detail and simulation speed. Coupled simulations or cosimulations aim to fulfill these needs by modeling multidomain systems across multiple simulation tools, while acting as one integral simulation platform that addresses the study [4].

Up to today, cosimulation (sometimes also referred to as *combined simulation* or *cooperative 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 (simulation program with integrated circuit emphasis-type) circuit–EMT–stability simulations [6], and parallelized EMT simulations on workstations [7], [8]. These approaches, however, did not implement the overall system as models distributed into separate simulation processes. In [5], for instance, a smart grid test setup was simulated in real time. This was a multidomain system under test being solved inside a particular fixed-model framework, i.e., an electrotechnical (monolithic) continuous simulation. Pure cosimulation separates the models and the various solvers and focuses on the coupling between the processes. Such a distributed approach would be of great advantage for smart grids particularly, as arbitrary distributed systems are interconnected via ICT or physical links.

These considerations for cosimulation require the integration of simulation tools for intelligent electric power systems beyond the state of the art. No fully fledged alternative assessment method is available. Experiments are expensive, time consuming, and often restricted by the laboratory facilities. This is challenging, especially for intelligent electric transdisciplinary power systems. And while monolithic multidomain simulators allow assessing such systems, this is at the cost of system scalability and suboptimal numerical algorithms [9]. This gives rise to various challenges for cosimulations, such as

- refined simulation, system testing, and validation procedures (e.g., success parameters)
- hardware-in-the-loop (HIL) treatment (e.g., controller and amplifier interface standardization, harmonized data structures, and 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
- model and simulation coupling algorithms (i.e., numerical algorithms).

These challenges signify the need for a clear positioning of various aspects and implications of cosimulation in terms of power system assessment. This article, part 2 on cosimulation of intelligent power systems, covers the application to test cases that span various

Over the past decade, profound efforts have been made to couple continuous power system simulators with discrete communication network simulators.

domains. This article 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 metalevel dimension to the heterogeneity challenge [10], [11], are outside the scope of this article.

Figure 1 shows a system under test inside the distribution system. It consists of a photovoltaic (PV) 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 needs to be undertaken. Defining the actual test setup for assessing these criteria is a challenge. Nonvirtual (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 even disregarded. 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. Cosimulations allow virtual and nonvirtual elements to be combined by interfacing refined domain-specific tools or even to go one step further and attach real controllers or power HIL (PHIL). Figure 1 shows how a typical cosimulation test setup can be achieved to accurately handle the higher level controls for this particular case.

ICT and Power Systems

ICT is playing an ever more prominent role in power systems. Developments such as the Internet of Things, smart homes, and vehicle-to-X communication further contribute to a data-driven power system. The use of ICT in power systems has many 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 cosimulation to investigate the mutual influences of ICT and power systems and, therefore, the behavior of intelligent power systems has become significant.

Noteworthy applications of cosimulation 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, cosimulation can conveniently scrutinize interactions between completely different systems. For instance, the impact of communication latency on the power system was analyzed in [17], while the impact of cyberattacks on the electric power grid was studied in [18] and [19]. Cosimulation has also proven to be useful in exploring artificial intelligence applications in power grids [20]. In addition, there has been extensive work done on combining classical and factory automation standards with power systems [21], which increases the need for this type of cosimulation. Real-time HIL test beds have been proposed for automation-related cosimulations [22], but nonreal-time versions are expected to provide further insight into these systems. Setups as 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] was 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 cosimulation framework (GECO) [25] for evaluation of wide-area monitoring and control schemes integrates Positive Sequence Load Flow Analysis software 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 cosimulation of power and ICT systems for real-time evaluation (INSPIRE) [26] uses the high-level architecture (HLA) (IEEE 1516) [89] for time management, providing a cosimulation platform for modeling the effects of ICT infrastructures on power grids. Table 1 provides a nonexhaustive list of examples of cosimulation of power systems and ICT infrastructure.

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

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 a best-effort basis (i.e., no communication speed or fidelity is guaranteed by the respective protocols). The associated applications have either a guaranteed latency and throughput or a more relaxed use. Regardless of these bounds, the real-time guarantees might be needed at different time scales. An IEEE C37.118 [90] for Phasor Measurement Unit (PMU)-based monitoring system, for example, needs fast and guaranteed transport. International Electrotechnical Commission (IEC) 61850, [91] an Ethernet-based communication standard for

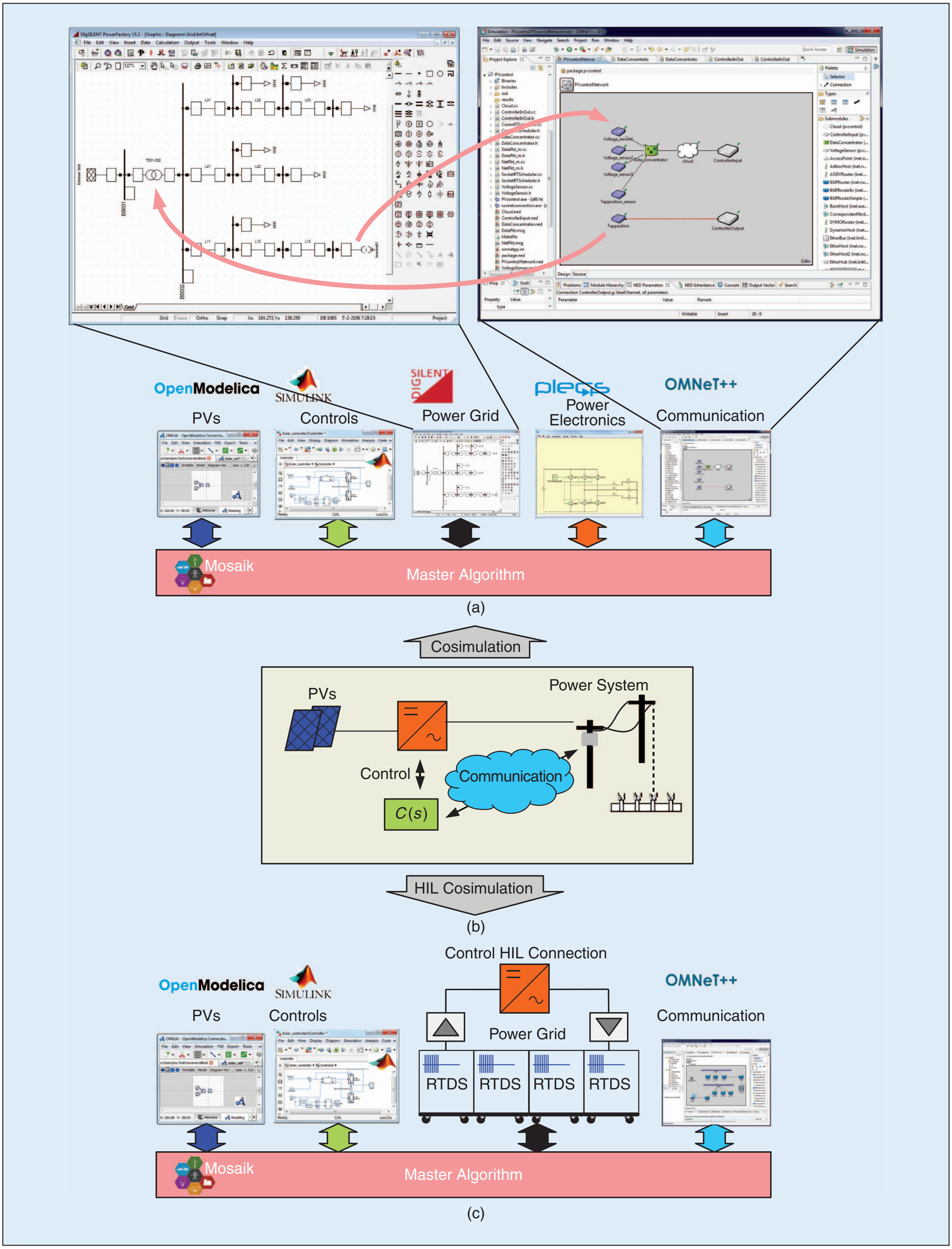

FIGURE 1 – (a) Analyzation conducted in a full cosimulation fashion for (b) a use case with an inverter-coupled PV plant, a communicating controller C(s), and a distribution grid. (c) The analyzation conducted for (b) in real-time with the real inverter in the loop. RTDS: real-time digital simulator.

TABLE 1 – SOME EXAMPLES OF COSIMULATION OF POWER SYSTEMS AND ICT INFRASTRUCTURE.

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 and 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]	Cybersecurity 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 and NS-2 [31]	Distributed energy resources integration	OpenDSS, NS-2	Not addressed	From milliseconds to seconds	Medium size
TASSCS [19]	Cybersecurity of SCADA	PowerWorld, OPNET	N/A	Real time in communication network	Suitable for large systems

N/A; not available. OpenDSS: Open Distribution System Simulator; OMNeT: Objective Modular Network Testbed in C++; TASSCS: testbed for analyzing security of SCADA control systems; SCADA: Supervisory Control and Data Acquisition; PSCAD: power system computer-aided design; EMTDC: electromagnetic transients including dc; VTB: virtual test bed; OPNET: optimized network engineering tools; DIgSILENT: digital simulation and electrical network.

substation automation systems, combines real-time and best-effort services such as generic object-oriented substation event (GOOSE) and manufacturing message specification (MMS).

Based on the prior discussion, it is evident that the flexibility of cosimulation potentially allows for a mixture of the ICT and power components as well as systems for different time scales, even in real time. As shown in Table 1, there are examples of cosimulations that consider different time scales according to their specific application. For phenomena that involve loose real-time guarantees and long time scales, e.g., advanced metering infrastructure reading, it would be possible to choose the interfacing and synchronization methods introduced in part 1. However, for phenomena that involve strict real-time guarantees and short time scales, e.g., PMU-based monitoring, it is a challenge to design capable interfaces and appropriate synchronization methods. Real-time cosimulation techniques based on powerful real-time simulators are needed under such circumstances, as will be detailed in the next section.

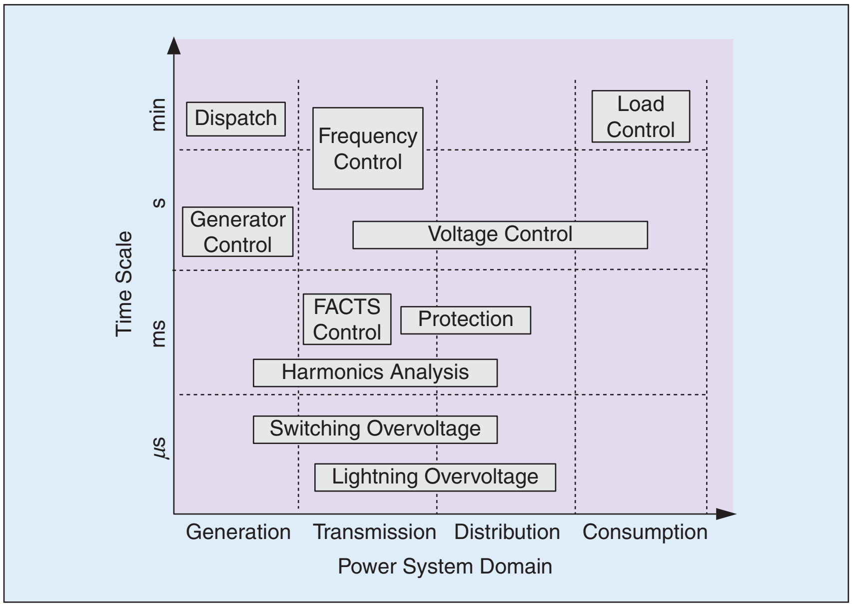

FIGURE 2 – The time scales of various power grid applications based on [32, Fig. 4].

Real-Time Simulation for Intelligent Power Systems

If the simulators compute the model time as fast as a wall clock, real-time simulation is possible. The main reason behind this 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 a real-world clock. Real-time simulations applied to the domain of intelligent power systems can be classified in two categories: offline and HIL real time. 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 or power electronic device). Thus, for HIL simulation, a digital real-time simulator (DRTS) with interfacing capabilities for connecting external devices is required. HIL simulation can be classified into two types: controller HIL (CHIL) simulation and PHIL simulation. Figure 4 shows the basic implementation structure of both CHIL and PHIL simulation.

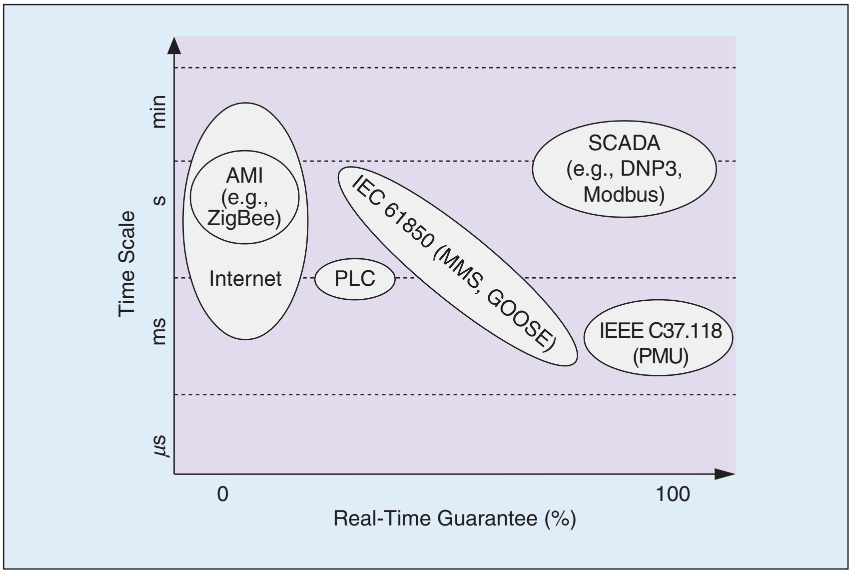

FIGURE 3 – The real-time guarantees and time scales of power system communication protocols. AMI: advanced metering infrastructure; DNP3: distributed network protocol; PLC: power-line communication.

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 in the early stages of design for testing controllers 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, a sensor, and the HUT. The amplifier provides the operating power to the HUT based on the low-power input signals from the DRTS, while the 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:

- *DRTS*: Industrial-grade simulators such as the 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 on the order of microseconds. Table 2 summarizes the features of different real-time simulators used for power engineering applications in terms of the interfacing methods used, the type of hardware used, the communication protocols supported, the 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 such as 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 the accuracy and stability of a PHIL simulation. Figure 5 shows an example of an interface algorithm called an *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 because of the ease of implementation, but its stability depends on the source-to-load impedance ratio. Alternative algorithms are reported in [33], [35], and [36].

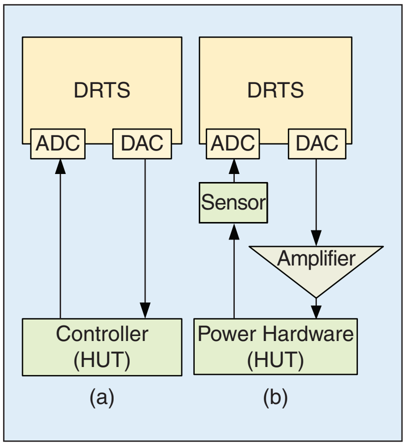

FIGURE 4 – The basic structure of (a) CHIL simulation and (b) PHIL simulation.

Many multidomain and multiphysics applications of HIL simulation integrated with cosimulation can be found in the literature for diverse fields of engineering.

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 the 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. The following are among the noteworthy applications:

- *Relay testing*: This is one of the oldest and most popular applications of HIL simulation and is presently used for the design, study, and testing of relay coordination and for distance relay protection [37].
- *Test bed for control strategies*: With the availability of different communication protocols such as TCP/IP and standards such as IEC 61850, C37.118, PMU, and DNP3 incorporated in the DRTS system, it is possible to develop real-time test beds 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 such as energy management schemes and simulation of cyberattacks [38], passive islanding studies based on PMU data [39], testing of power control of wind parks with energy storage [40], test beds for the control design of microgrid energy management systems [41], and the design and validation of wide-area control systems [42].
- *Design, testing, and validation of power electronic devices*: With the availability of high-performance input/output terminals of resolutions 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 test beds to analyze the impact of plug-in hybrid electric vehicles on the grid [45], PHIL test beds for HVdc systems [46], and PHIL test beds for grid integration analysis of PV inverters [47].

Real-Time Cosimulation of Intelligent Power Systems

Many multidomain [48] and multiphysics [49] applications of HIL simulation integrated with cosimulation can be found in the literature for diverse fields of engineering. In [48],

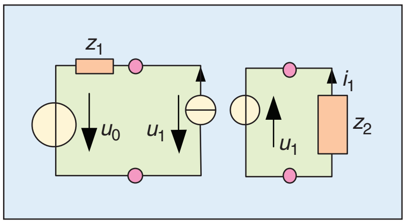

FIGURE 5 – The ideal transformer method for interfacing power hardware and a DRTS.

TABLE 2 – A SUMMARY OF THE FEATURES OF REAL-TIME SIMULATORS FOR POWER SYSTEMS.

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	IEC 61850, TCP/IP, IEEE C37.118, PMU, DNP3	Dommel's algorithm-based nodal solver	RSCAD
eMegasim from OPAL-RT Technologies Inc.	Multicore CPU, FPGA, commercial-off-the-shelf motherboard	Shared memory, Gigabit Ethernet, Dolphin networking, FPGA-based analog and digital I/O terminals, supports third-party I/Os	IEC 61850, IEEE C37.118, DNP3	ARTEMIS-SSN, discrete Simulink Solvers	Simulink, C/C++, MATLAB, Fortran wrapped in S-function
HYPERSIM from OPAL-RT Technologies Inc.	SGI Supercomputer with SGI and Intel CPUs	Gigabit Ethernet, Standard PCIe interface with DSP-based ADCs and DACs	IEC 61850	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 [92]	Typhoon schematic editor, SpiceShuttle, MATLAB	Typhoon Software Suite

FPGA: field-programmable gate array; CPU: central processing unit; I/O: input–output; TCP/IP: transmission control protocol/Internet protocol; RISC: reduced instruction set computing; ASIC: application-specific integrated circuit; GTNET: giga-transceiver network communication card; DSP: digital signal processor; PCIe: peripheral component interconnect express.

a multidomain cosimulation procedure with HIL capability is proposed for the design and analysis of electric propulsion systems. A concept for a multiphysics PHIL test bed, as shown in Figure 6, is developed for the testing of renewable energy systems and is applied to domestic energy systems [49].

Considering the state of the art of computing, sensing, and communication technologies, it is reasonable to assume that HIL integrated with cosimulation capabilities will become a relevant tool for the study and analysis of future intelligent power systems. Applications of such HIL cosimulation test beds include analyzing distribution grids for demand response strategies [50] and testing of demand-side management techniques to provide ancillary services [51]. In [50], the virtual grid integration laboratory HIL cosimulation test bed 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 functional mock-up interface 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 cosimulation test bed introduced in [51] consists of a demand-side management module, a real-time simulator module (by Applied Dynamics International), and a microgrid module.

An HIL cosimulation test bed is developed in [52] using the HLA framework and the IEEE 1516 HLA standard. Figure 7 shows the proposed architecture with a runtime infrastructure (RTI) and three individual federates (a network simulator federate, a Power-Sim federate, and an HIL federate) facilitating the cosimulation environment. The power system simulator is connected to the Power-Sim federate via an object linking and embedding 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 the data exchange between the cosimulation and the virtualized execution platform. A PHIL platform with remote distribution circuit cosimulation 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-based data exchange protocol.

It is reasonable to assume that HIL integrated with cosimulation capabilities will become a relevant tool for the study and analysis of future intelligent power systems.

Real-time cosimulation 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 applications of such a platform is the study and analysis of methodologies for controlling and monitoring large power systems with PMU-based wide-area monitoring protection and control systems. Some of the efforts to build such a real-time cosimulation platform are as follows:

- *RTDS based*: In [54], RTDS is used for power system simulation, and the NS-3 network simulator is used

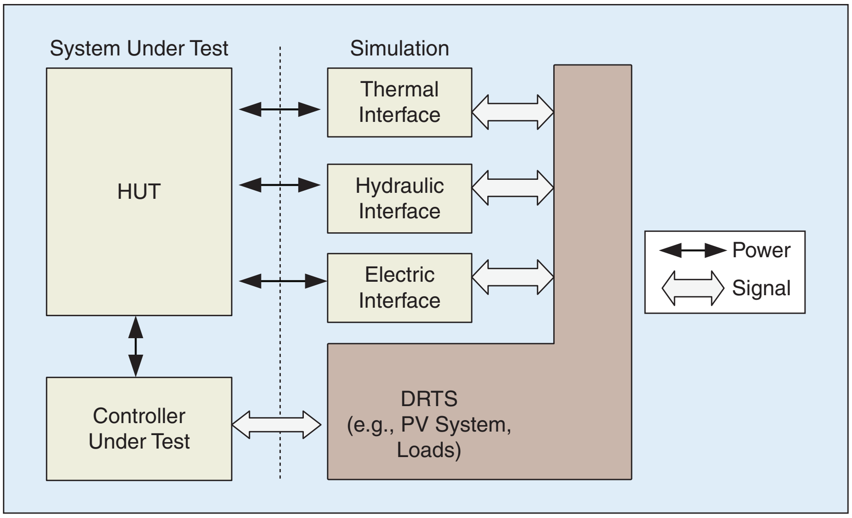

FIGURE 6 – The concept of a multiphysics PHIL platform based on [49].

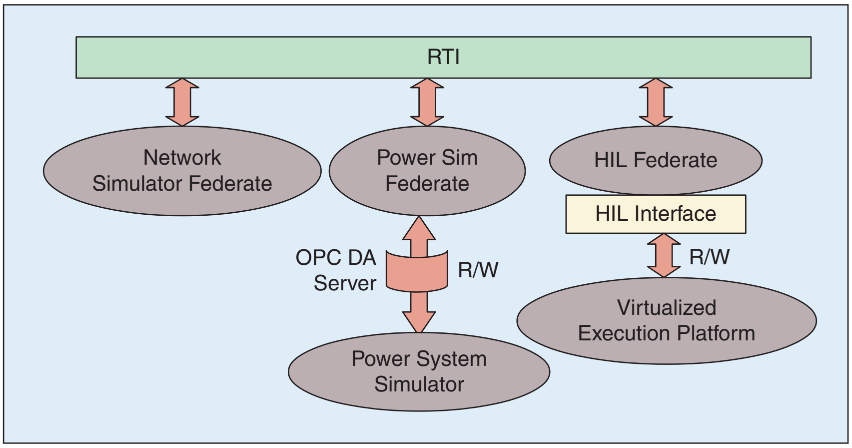

FIGURE 7 – An HIL cosimulation architecture based on [52]. R/W: read/write.

Developing large power grid models based on RTDS is rather expensive, since the hardware requirements scale linearly with the number of simulated nodes.

to simulate the communication system. This test bed 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 National Instruments Extensions for Instrumentation (NX PXI) as the interface. A real-time cosimulation test bed is developed in [56] for analyzing the impact of cyber events on microgrids using RTDS as the power system simulator and common open research emulator as the 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 cosimulation. The Orchestra application programming interface acts as the cosimulation scheduler and coordinates the components connected to OPAL-RT. In [57], this cosimulation 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 microgrid cosimulation 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 or software components through the OPC communication protocol and various APIs. In [58], the PowerCyber test bed is built using the integration of PowerFactory with intelligent electronic devices and remote terminal units to perform cyber-physical security testing.

A Use Case on Interfacing Stability-Type with EMT-Type Simulations

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 quasistationary models. Overvoltages, startup and inrush behavior, and harmonics were as a rule caused by local devices and passive network components. This allowed considerable network reductions for the EMT simulation. The main simulation tools were transient stability (TS)-type simulations and EMT-type simulations.

The introduction of power electronic-interfaced devices and transmission systems brought a different perspective to these paradigms. Line-commutated HVdc transmission, especially, 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-type [61] and stability-type simulations [62] alike.

In the 1980s, a widely accepted approach to include detailed HVdc converter behavior into stability-type simulations was published [63]. In this article, the TS-type simulation acted as the master simulation and engaged a quasistationary 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

- generalizations on the EMT network segment type [64], [65]
- generalization on numerical implementations such as event handling [66]
- interaction protocols [67]
- parallelization [68]
- accuracy improvements [69]
- dedicated interfacing techniques for voltage-sourced converter-based HVdc (VSC-HVdc) links [70], [71]
- advanced treatment of sequence components [72]
- refined decomposition methods for assessing the TS problem [73].

Interfacing TS and EMT Simulations

In terms of the taxonomoy of part 1 of this article, interfaced EMT-type and stability-type simulations can be categorized as cosimulation, 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, for instance, can apply a wide variety of solution methods for solving the set of differential-algebraic equations (DAEs) (e.g., implicit versus explicit solvers and 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

An easy way of implementing a power system electrotechnical cosimulation is to set the transient-stability simulation as the master orchestrator.

of differential equations is discretized and mapped to the trapezoidal rule of integration. Notwithstanding the categorization into a multidomain, multisolver type of simulation, power system electrotechnical cosimulations are commonly referred to as hybrid simulations, mainly for legacy reasons. To prevent inconsistencies, we abide by the term *cosimulation*.

Stability-type and EMT-type cosimulations 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
- 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 to a large extent determines the accuracy of the combined solution: the larger the detailed subsystem, the higher the level of detail that can be achieved (e.g., unbalanced conditions and harmonic distortion). This, however, also increases the computational burden, which is one of the main benefits of TS and EMT cosimulations.

To facilitate interfacing information about flow and effort between the subsystems, either one needs to be represented into the other. As a rule, this is done by dynamic Norton or Thévenin equivalents, which dictate during the communication step (see part 1 of this article) a voltage source or current injection based on the system quantities available at t_k. Generally speaking, for the representation of the detailed subsystem into the external subsystem, this is the transformation of point-on-wave currents and voltages to positive-sequence quasistationary phasors. However, including the external subsystem dynamics into the detailed subsystem 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. The determination of these is far from trivial and commonly involves coherency determination [76], among other cases [77].

An easy way of implementing a power system electrotechnical cosimulation is to set the TS simulation as the master orchestrator, thereby embedding the EMT-type simulation into this main simulation by an inner calculation loop. This algorithm is shown in Figure 9 and is implemented in [70]. At t_0, the overall simulation starts with an ac/dc power flow, thereby initializing the network, device, and interface models for both the external and the detailed subsystem [78]. As the stability-type simulation acts as the master, the 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 toward the detailed subsystem typically entails the following steps:

1) Fetch the 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 the causality conditions.

Subsequently, the detailed subsystem executes its minor time steps until reaching the condition $t_{\mathrm{emt}} = t_{n+1}$. 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 point the master (TS) simulation advances the overall time step. The above sequence follows

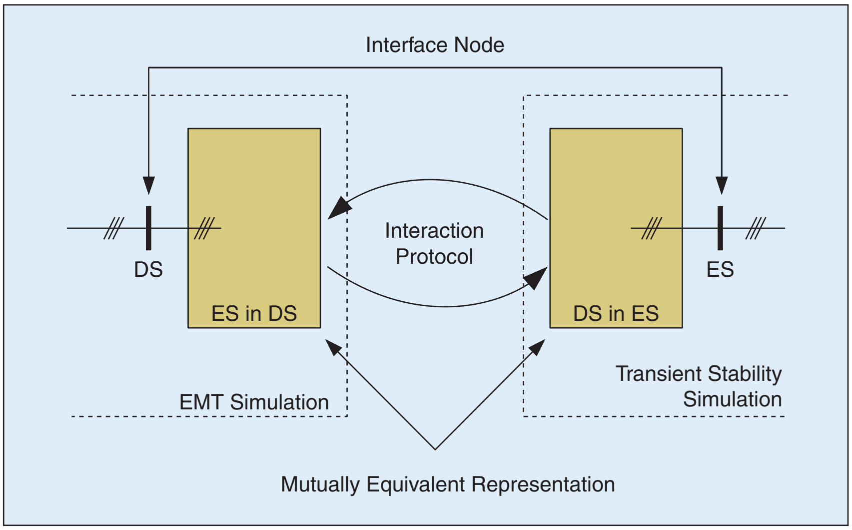

FIGURE 8 – A detailed and external subsystem coupling for EMT–TS cosimulations. DS: detailed subsystem; ES: external system.

Even if the interface is frictionless, the models themselves are often challenging with respect to scalability and performance.

the serial (Gauss–Seidel) communication sequence and makes up a weakly coupled simulation. A similar calculation sequence is applied in commercially available simulation packages such as 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. For instance, when the master or one of the simulation federates does not support rolling back in time, using adaptive time-step sizes or model-specific mockup services such as derivative determination, the capabilities of the cosimulation as a whole are inhibited.

Cosimulation Implementation for VSC-HVdc

The next generation of HVdc transmission based on VSC-HVdc has the potential to transmit power in the gigawatt 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 cosimulation applications. This section gives a survey of the functionality requirements of the cosimulation environment.

From an operational point of view, VSC-HVdc links can be separated mainly into three types: offshore wind power plant connections, VSC-HVdc links embedded in one synchronous area, and multiterminal schemes. The control design of point-to-point links focuses primarily on 1) conveying the active power infeed toward 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. Multiterminal schemes do not comply very well with this concept, as dc faults should be cleared selectively, the direction of active power flow should be controllable, and sophisticated fault ride through and/or ancillary services must be engaged.

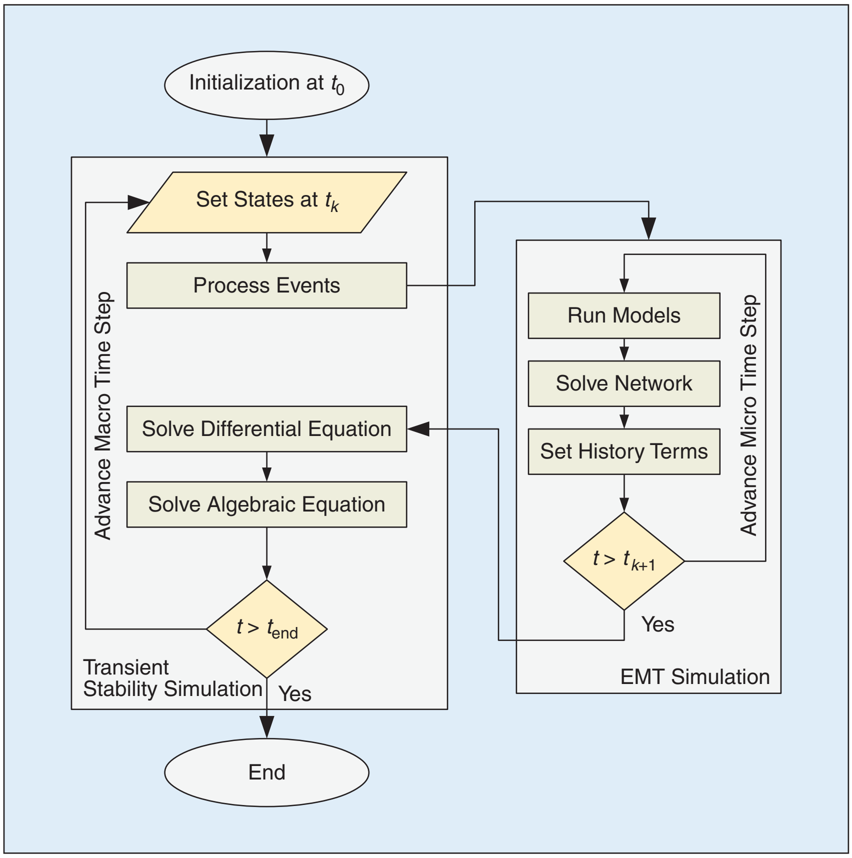

FIGURE 9 – The workflow of an electrotechnical EMT–TS cosimulation, in which the TS simulation acts as the master simulator.

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 in turn inflict severe perturbations in the power output. Such events necessitate the inclusion of a wide spectrum of physical phenomena in 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 in the overall system assessment is made more effective by using a dedicated domain-specific model and a corresponding solution algorithm.

The relatively fast inner control loops of VSCs needed the 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 (ES), at least for power frequency but preferably also for higher harmonics [76].
- *The extrapolation procedures for the ES quantities into the detailed*

subsystem: Voltage angles and magnitudes are synchronized as algebraic variables, which allows for discontinuous jumps at synchronization instants. Extrapolation estimates the trace of these quantities, leading to a more realistic VSC-HVdc model response.

- *Improving causality conditions for the extrapolation steps*: At faults, especially, 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.
- *Phasor capturing methods for small time step-size conditions*: Notably during small or adaptive time step-size conditions, the discrete Fourier transform needs values from the detailed system and from previous synchronization points, e.g., t_{k-1}, t_{k-2}; the interaction protocol has to account 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 cosimulation is contained in the external subsystem. 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 [70] that changes the calculation sequence during events. The figure shows two timelines 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 circled numbers indicate the simulation and interfacing actions conducted by the cosimulation. The normal calculation sequence is first to run the external subsystem, thereby enabling advantageous causality conditions for the detailed subsystem's source magnitude and angular interpolation, and then to provide output to the detailed subsystem, run it, and interface the obtained phasors back to the external subsystem.

For Figure 10, 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 or extrapolated. Therefore, the calculation sequence is adapted to first prioritize the detailed subsystem (i.e., ② and ③) using zero-order hold values of the source quantities obtained at ①, hence providing its undelayed response to the external subsystem ④. Then the simulation advances toward t_{n+1} (i.e., ⑤) while using the same phasor quantities as in 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 responses right after faults, 2) enables causal interpolative filtering, and 3) shows favorable accuracy characteristics against a full EMT reference simulation.

Is there hope for a unified modeling language for all aspects, ranging from EMT up to market mechanisms?

Conclusion and Outlook

This article gives the latest developments in cosimulation of intelligent power systems. The aspects of discrete and continuous models, of HIL simulations and of applying cosimulation in a complex power system setting are covered. Cosimulation has several advantages when working with intelligent power systems: proven tools with validated models can be used, virtually every style of heterogeneity (e.g., multirate 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 to create a smart grid simulation platform. Table 3 shows a nonexhaustive list of properties of three popular smart grid cosimulation federates. Their features and interfaces are far from being harmonized, which is the typical situation where a set of tools is expected to form a joint, hybrid simulator. Therefore, the integration task consists not only of writing drivers or interface wrappers but also of semantic efforts (e.g., representing events in a nonevent simulator, interpolating or extrapolating between time steps, and so forth).

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 be solved only with a carefully developed model where the designer

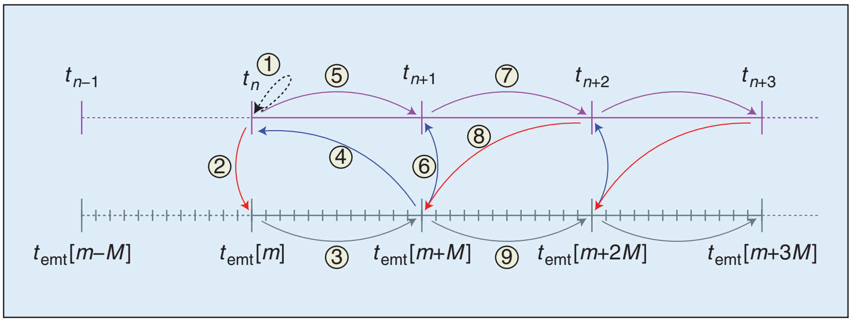

FIGURE 10 – An interaction protocol change in the event of faults inside the ES.

How can models be documented, so that revisions, details, and collaborative work can happen over a long period of time?

is well aware of the time constants, events, and dependencies.

The most urgent topics that require research are as follows:

- *Languages*: Is there hope for a unified modeling language for all aspects, ranging from EMT up to market mechanisms? Do languages like Modelica move in the right direction? Currently, these languages lack 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 period of time? This is a topic well known in software and collaborative development. Currently, there is no established, easily deployable method of documenting and tracing complex projects such as power system cosimulation.
- *Formats*: Which standards are the most promising for time series, parameters, libraries, or components [83]? Emerging standards like Hierarchical Data Format 5 (HDF5) and extensible-markup-language (XML)-based industry standards should be sufficient for these needs. Many tools, however, still use comma-separated value lists and other nondescriptive formats.
- *Distributed computing*: How can we split large systems into parts to run them in 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 hardware versus the compilers and software are balanced against each other. Most known parallel attempts use nodes connected via general-purpose communication networks, which is a far cry from true parallel computation.
- *Multigranular models*: How can we define models with different levels of detail 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 versions of the component behavior, e.g., a static, a linearized, and a detailed version. 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 have memory (which digital controllers and software in general do). The number of system states explodes, and validating system behavior becomes difficult. 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 about 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. While it has gained substantial acceptance in other domains, it unfortunately did not achieve much resonance in the power domain, except with its use in InterPSS, the

TABLE 3 – A COMPARISON OF COSIMULATION-SPECIFIC PARAMETERS OF THREE POPULAR TOOLS.

	POWERFACTORY	OPEN MODEL ICA	OMNET++
Domain	Power system (power flow, TS, EMT)	Multidomain,multiphysics	Communication, ICT, agents
License	Commercial	Open source (GPL derivative)	Open source (GPL derivative)
FMI model exchange	N/A	Import and export	
FMI cosimulation	Power flow only	Only master simulator capable	
RT capability	RT flag	N/A	Native
Model/project data format	Binary	XML, text	Text
API cosimulation compatibility	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

GPL: general public license; FMI: functional mock-up interface.

Common Information Model, and some academic projects.

- *Numerics*: How do uncertainties in input data or model data propagate through cosimulation? 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 are active fields of research [85].
- *Validation*: How can we validate results when a monolithic simulation is no 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. Cosimulation can simulate systems that are too large for monolithic, validated tools, which therefore cannot serve as a validation benchmark [86]. The only workaround available for this dilemma is to use a mix of experiments and different flavors of cosimulation to validate the simulators against each other [87].

Cosimulation is the method of choice if power systems are heterogeneous and/or large. Its ability to combine entirely different submodels makes this method attractive for cases such as power-to-heat, electric mobility, transmission–distribution interplay, and 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 multiphysics manner and still be fully integrated in a power systems analysis. Still, the above challenges require intensive work and research to fully exploit the idea and benefits of cosimulation for intelligent power systems.

Acknowledgment

This work was partly supported by the European Community's Horizon 2020 Program (H2020/2014–2020) under the project "ERIGrid: European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation, and Roll Out" (grant 654113).

> **How can we validate results when a monolithic simulation is no longer possible and therefore no benchmark exists?**

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