Real-Time and Co-Simulations for the Development of Power System Monitoring, Control and Protection

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Abstract — **Research, development and validation of power system monitoring, control and protection applications requires manifold simulation tests before implementing solutions in the real system. While many applications can be investigated with conventional steady-state or dynamic simulators, more complex solutions and especially prototypical implementations require real-time or co-simulations. Co-simulations are able to simulate the interaction between power and ICT-systems. Real-time simulators provide data similar to measurement data streams in real systems. They are particularly useful for hardware in the loop tests. The paper gives an overview on theoretical principles and introduces several setups and applications of real-time and co-simulators for the development of power system monitoring control and protection applications. Additionally, Smart Grid testing environments based on real-time and co-simulators are presented.**

Index Terms — **Real-time simulation, Co-simulation, power system monitoring, control, protection**

I. INTRODUCTION

Due to increasing market interactions and integration of renewables, the power grids are operating closer to stability limits. The manifold integration of power electronic devices, like the renewable energy systems, but also control devices like FACTS and transmission components like HVDC require new and fast acting monitoring, control and protection schemes. Power electronic converters with complex control principles demand specific development and testing setups. The overall system coordination with and between all these devices leads to complex setups, which need to be tested in detail before their practical implementation. Hence, the challenges and applications for power system simulation are manifold. Besides power flow calculations for steady-state power system planning purposes, dynamic simulations are used to investigate stability phenomena such as transient stability, voltage stability or frequency stability. Monitoring, control and protection applications can be implemented in such simulation environments for research purposes and to demonstrate their principle behavior.

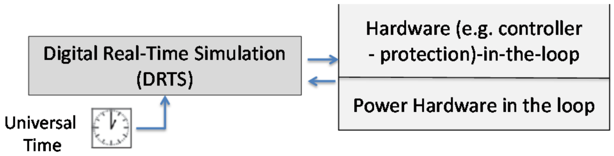
However, all the effects of the hardware implementation cannot be taken into account in classical offline simulations. This holds particularly true for power electronic converters and fast acting control and protection. The control hardware has to be tested on a simulated system model or on the device to be controlled, especially in an advanced stage of prototype development. In such cases, hardware in the loop implementations of these prototypical setups, together with real-time simulators, are necessary.

For fast acting system functions, like wide-area or coordinated system control or protection applications, the information and communication (ICT) environment has to be considered and modelled or implemented appropriately. Co-simulation of power system dynamics and ICT-systems is required. Wide area monitoring, control and protection functions (WAMPAC) are an example in which the proper modelling of delay times, caused by the ICT-system, have a significant impact on the performance of the solution. Since all control functions with remote measurements or actions fall into this category, the ICT must take them into account to reach practical solutions.

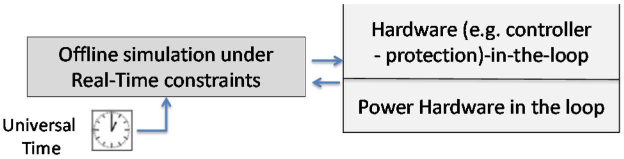
Due to trends like the transition towards ICT-based smart grids, it is becoming more and more important to interface different specialized simulators to understand the joint system behaviour across multiple domains. Simulations of intelligent interconnected energy systems require models from many different fields e.g., highly sophisticated simulation models for electrical grids or information and communication (ICT) system models [1][2]. When simulating these domain-specific models, potential techniques may be distinguished into four categories:

- Real-time simulation (Figure 1a); simulating a model of a specific representation (e.g. differential equations, discrete automata) within a dedicated runtime environment (solver). The software is developed to guaranty a specific and stable time for the computation. This computation can be time stamped with a clock linked to the universal time, which makes it possible to interact with hardware. If the hardware device to be tested needs a comparably low signal level, like controllers, intelligent electronic devices (IED) or protection devices, Hardware-In-the-Loop (HIL) is used. If power amplifiers are needed for power equipment testing, Power-HIL is used. Models may be divided and run in parallel on multiple solvers to speed up computational time.
- Offline simulation with real-time constraints (Figure 1b): For slow applications, it is possible to achieve an interaction between an offline simulation and some actual device. Since the computation time is not always constant for such applications, the time period of the interaction between the simulator and the hardware must be larger than the maximum time for computation. In this case, it is possible to use any offline simulator, which may be very effective. This avoids the conversion between offline and real-time simulation, which can often induce some discrepancies.

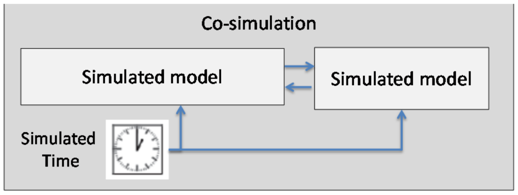
- Co-simulation (Figure 1c): Hybrid simulation models (power system, ICT ...) and different representations are executed in individual runtime environments. Synchronizing this potentially complex setup of heterogeneous models and their individual solvers is a particular challenge in co-simulation. One single clock is needed but, since no hardware is involved, it is not mandatory to use the universal time.
- Real-time co-simulation (Figure 1d): Same as co-simulation but some hardware devices are involved, so the clock must be linked with the universal time.



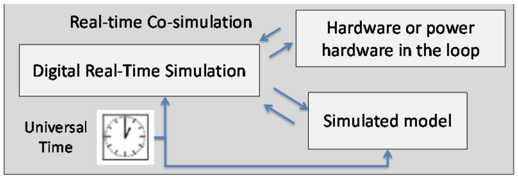
a) Real-time simulation



b) Offline simulation with real-time constraints



c) Co-simulation



d) Real-time co-simulation

Figure 1: Overview of real-time and co-simulation

Depending on the type of application, either real-time simulation or co-simulation is needed and set up accordingly. In either case, must be decided which part of the system is implemented as hardware and which is simulated in real-time. This paper presents several approaches for real-time and co-simulations.

For both real-time and co-simulation the theory is presented in brief. Then, implementations and applications to power system monitoring, control and protection are introduced to demonstrate the value of these simulation approaches.

II. REAL-TIME SIMULATION

A. Introduction

For the design and validation of hardware prototypes Digital Real-Time Simulators (DRTS) offer the advantage of a safe and relatively cost-efficient testing environment. Real-time means that a system specific simulation time step (STS) range is guaranteed and that all required simulation activities are processed within this time interval. In the context of power system simulation, this implies that the time step size considers system dynamics such as transients. The simulator's signal conditioning is acceptable only if the DRTS performance respects the pre-defined STS without false interpolations caused by overruns.. The DRTS provides analogue or digital interfaces that are directly interconnected with the Device Under Test (DUT). Interfaces can either be analogue current and voltage or digital communication links, such as based on TCP/IP.

In case the DUT interacts with the simulation model, the technical term is Hardware-In-the-Loop (HIL) test. This means that the DUT's response triggers events within the simulation process and thus impacts the signal generation. Furthermore, such tests offer the benefit of an unlimited amount of test scenarios for extensive sensitivity analysis. In contrast to tests within the real target environment, more extreme use cases that might increase the risk of severe damage to valuable system assets can be considered. In addition, the complete test process can be automated without the need for interdisciplinary expert knowledge and with fewer resources. In some cases, the DUT may be a power electronic converter or a system needing some power exchange , which requires a high bandwidth amplifier between the real-time simulator and the equipment. This is the concept behind Power Hardware in the Loop.

Formerly, the applications of digital real-time simulation were mainly orientated toward transmission grid needs, such as: protection tests, thyristor HVDC or SVC hardware control validation. Currently, real-time simulation has moved to distribution system applications due to the development of smart grid and micro grid studies. The increasing integration of power electronics with transistors represents an important challenge for real-time simulation since, in this case, an accurate switching model is needed. Due to the very small time step needed to obtain an accurate model, FPGA is a good tool for this type of application, while other types of applications do not require such high performances. Tests for EMS applications, for example, do not need to actualize the information at a higher speed than the EMS software can manage. In this case, phasor real-time simulation can be sufficient. In certain applications, different tools may be used at the same time; for example a phasor simulation may be connected to an EMT simulation or FPGA connected with EMT simulation.

B. Major Concepts of Real-Time Simulation

The main objective of real-time simulation is to connect and test a piece of real hardware, a device-under-test (DUT), to a computer-emulated system and execute both at the real world speed. To create such a setup, the system, usually described by a set of algebraic differential equations (DAE), (i) has to be iterated on a high-performance computer to achieve real-time execution using (ii) specialized DAE solvers and (iii) there must be a software-to-hardware interface. This interface usually consists of a set of digital and analog input/outputs converters. The interface may, for example, also consist of Ethernet connections, in power system controllers that have IEC-61850 interface.

Custom-made computational hardware has long been required to perform digital real-time simulation of power grids [3][4][5]. In recent years, the increased computational power of commercial PCs makes it possible to run power system real-time simulations on commercial-of-the-shelf, multi-core PCs [6][7]. Despite recent advances in technology, the real-time simulation of large power system systems still requiresthe use of multi-core processing.

The best-suited DAE solvers to perform time-domain real-time simulation are of fixed time-step type, based on the nodal admittance method (often called Dommel method) and are used in simulators such as Hypersim [8][9][10] and RDTS. eMEGAsim [7] also uses a nodal admittance solver called State-Space-Nodal (SSN). As the name suggests, the SSN method merges a state-space method and the traditional Dommel method.

a) Power transmission systems

In case of transmission system applications, it is possible to take advantage of existing natural delays on long transmission lines to create subsystems that can be solved independently. This property allows dividing the network into subsystems with smaller admittance matrices, which can be solved in much shorter time. The resulting simulation model structure is illustrated in Figure 2 where the line equations serve as links between the decoupled sets of equations. Each set of equations can be attributed to a separate processors without introducing errors. In Hypersim, the partition of the grid is done automatically for a very large system, close to 1000 3-phase buses.

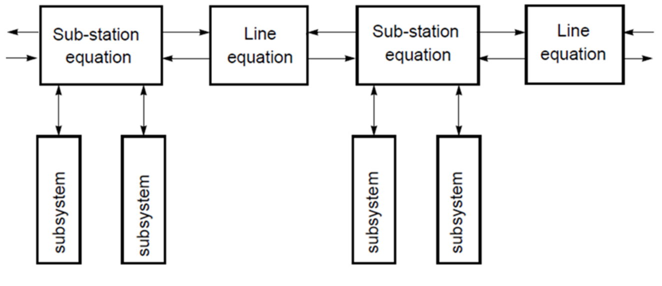
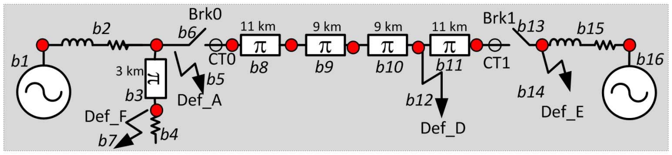


Figure 2: Parallelization of transmission system equations with transmission lines

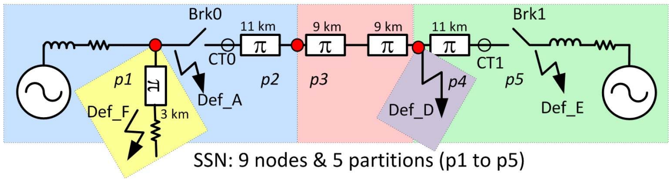
b) Lumped distribution power systems

The parallelization techniques used in transmission systems, based on the natural delay of Bergeron-type line models, cannot be used in typical distribution systems because they do not have long transmission lines: this type of system can also be described as lumped. This makes the real-time simulation very difficult. The State-Space Nodal method can provide a solution to this problem.

The main difference between Dommel and SSN solvers lies in the ways the different branches of the power systems are defined and solved. Both methods use the same nodal admittance method to solve the equations. In Dommel-like methods, users build the power system from a pre-determined set of electric branches (R, RLC, sources, transformers, etc...) and each connection point of these element becomes an interface point whose voltage must be solved simultaneously using the nodal admittance method. In SSN, by contrast, the user selects the unknown nodal voltage points from a general graphical description of the power system. In turn, these selected nodal points define distinct partitions of network elements. The partitions are just multi-port generalized branches whose equations are derived directly from their state-space description. SSN builds a nodal admittance matrix in the same way as Dommel's, only the branches are not defined a priori. Therefore, one advantage of SSN is that the user can choose the number of nodal voltage points, thus limiting the time to factorize the admittance matrix and speed up calculations. In the case of lumped distribution grids, SSN is able to solve their system of equations, without delay, and with up to 5 times more equivalent nodes than Dommel's counterpart [12][13], by virtue of the smaller size of admittance matrix to factorize and the parallel-thread-based solution of the SSN branch equations.



EMTP/Hypersim/RTDS: 30 nodes & 16 branches (b1 to b16)



SSN: 9 nodes & 5 partitions (p1 to p5)

Figure 3: Nodes, branches and partitions in EMTP and SSN

Figure 3 shows an example of a small distribution system in which all the transmission lines are short (3-11km). With such short lines, the line model cannot be of Bergeron-type and π-type line model must be used, with the effect of lumping the entire electric system (i.e. there is no delay to exploit during the EMT simulation of such network). Figure 3 compares the SSN and other EMT approaches in this regards. The upper part of the figure describes the model using pre-defined branches of typical EMT-type software, resulting in a network of 16 branches and 30 nodes. The bottom part of the figure shows the same network partitioned with SSN, producing a network with 9 nodes and 5 partitions. One key aspect here is that 'branch' and 'partition' concepts are exactly the same thing mathematically, a partition being only more complex than a basic branch.

The SSN approach has two major impacts on real-time simulations:

1- The admittance matrix Y is smaller in SSN than EMT type in software. Because matrix factorization is an $O(r^3)$ operation typically (r is the rank of Y), this therefore accelerates the most costly part of the EMT solution.

2- The large partition of SSN can effectively be computed in parallel (in the way of a parallel 'for' loop), using intra-step computer threads.

EMTP-like programs could also, in theory, do intra-step parallelization but the small size of the branch equations would make it ineffective considering inter-core processing delays. One must not confuse hardware inter-core delays (memory and threads communication delays) and algorithmic delays. The SSN algorithm has no delay, exactly like the EMTP.

c) Real-time Transient Stability solvers

Real-time solvers based on Transient Stability (TS) method have emerged. TS-based real-time simulators [14] are solvers that compute main frequency grid variables, such as RMS voltage and currents, and machine rotor angle and power flow. These real-time simulators can handle much bigger grids (up to 50000 nodes) than their EMT counterparts and are well-suited for voltage regulation studies, for example. TS solvers runs at time steps of 1 to 10 milliseconds and are therefore limited for the study of grid phenomena up to 10 Hz.

C. Applications of Real-Time Simulators

1) Example of Real-Time Simulation of Very-Large Grids

An application presented in [8] is a good illustration for super-large EMT real-time simulation. A simulation of the main part of Hydro-Québec's power system (Figure **4**) has been achieved. The main components of the model are:

- 643 3-phase buses
- 34 hydroelectric generators (turbine, AVR, stabilizer)
- steam turbine generators
- 25 WPPs
- 7 SVC
- 6 synchronous condensers
- 167 3-phase lines
- > 150 transformers including magnetic saturation

Modeling of large wind power plants (WPPs) is also presented with a decoupling technique for parallel processing (delay of transmission line not being always enough this technique consists of moving and grouping line capacitor or transformer inductance in certain conditions). Then, an aggregation technique for large WPPs [8] is validated. This model, validated in real-time simulation, could be used to study possible interactions between series-compensated power systems, real HVDC-controls and massive wind power generation

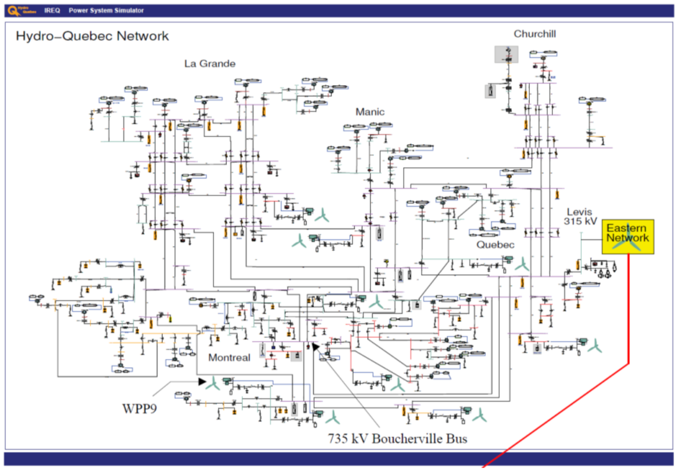


Figure 4: Model of Hydro-Québec power system [8]

The real-time simulation was realized in the Hypersim environment with an SGI supercomputer using 72 processors, at a 50µs time step. This application shows the high computational resources needed. For cost reasons, computational resources could be limited, which leads to limiting the size of the model. In this case, a part of the power system could be reduced with the aggregation of an area regrouping coherent wind-turbine generators [8].

2) EMT Real-Time Simulation for the Development of Future Protection Systems

While in the past only single functions have been tested separately to evaluate the characteristic behaviour of protection and control systems, this procedure no longer meets the complexity of modern protection and control systems. For this reason, application testing gains greater significance for modern power system protection.

Application testing for power system protection is defined as testing with transient signals from simulated power networks in a closed loop simulation. The current development of some state of the art protection evaluation systems shows a trend of adding the application test capability to these systems [15]. However, those platforms are designed to be mobile and they are not optimized for complex grid simulations. Therefore, DRTS with their high computational power and real-time capabilities are a superior alternative for application testing. In [16] an exemplary DRTS system manufactured by OPAL-RT Technologies and its various applications for power technology development are portrayed.

In [17] a hybrid DRTS-platform for combined protection type testing and application testing is presented. As proof of concept, a platform based on an eMEGAsim DRTS from OPAL-RT Technologies has been upgraded with IEC 60255-121 compliant type testing. The DRTS-platform offers the benefits of real-time power system modelling in MATLAB/Simulink® and powerful process automation using Python programming language. The principal scheme is illustrated in Figure 5 and the laboratory setup is shown in Figure 6.

The approach offers a new quality of service level and the possibility for comprehensive tests of sophisticated digital protection systems. In the first step, the rated frequency characteristic accuracy test, with a ramp of shots test pattern, was implemented. The overall test algorithm for the accuracy test is made up of 5 defined setup points, 7 fault cases and 10 test points with a ramp of 21 test impedances. In total, there are 7350 test steps which have to be performed. Therefore, an automation routine is required and implemented in Python. The rated frequency accuracy test was performed to prove the concept of the hybrid simulator. The results of this part of the IEC 60255-121 type test was compared to the results gained from the industrial relay test system ARTES 4.60 from KoCoS Technology Group. Figure 7 depicts one example test step for a single-phase fault.

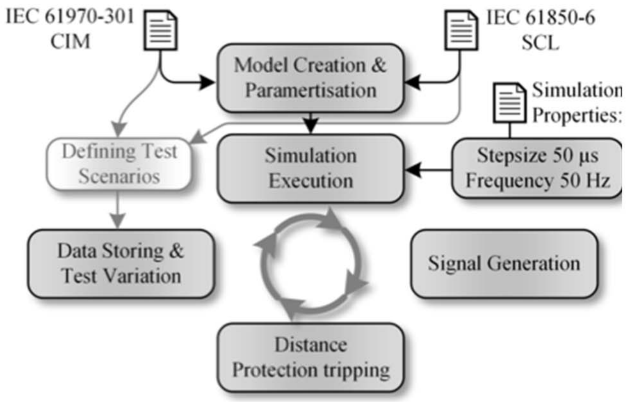


Figure 5: Principal scheme of automated type testing with real-time simulation and amplified signals for protection IEDs

The test voltage and current for the faulty phase is generated with a simulation step size of 50 µs. The Figure shows these quantities as low-level voltage signals. Additionally, the pickup and trip signals, which are generated from the DUT, are illustrated. The time delay between the pickup and the trip is 0.2002 s. Compared to the operating time delay of 0.2 s, there is only a minor error. The trip time is determined by the time difference between the first occurrence of the current and the trip signal. The trip delay is defined as the trip time reduced by the operate time, as shown in Figure 8.

This observation shows that the results from the real-time simulator provide less variation in the trip delay time. Furthermore, the automated type test is running free of interferences on the DRTS. The performed test was running on 1 of the 4 available cores without overruns. Therefore, the computational power limits of the DRTS are not reached yet.

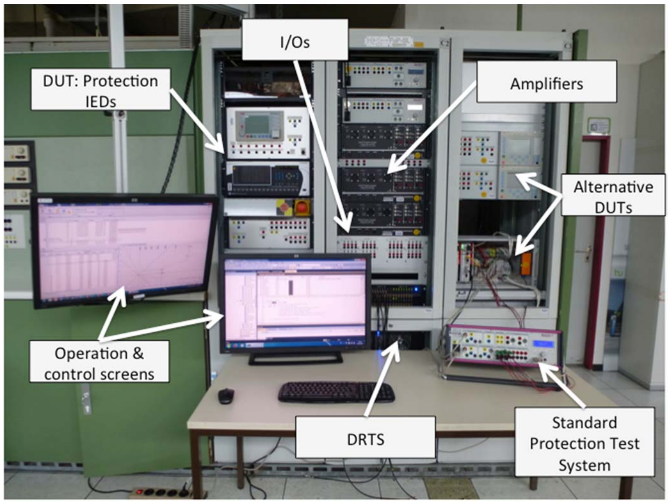


Figure 6: Laboratory setup of an HIL-test environment based on DRTS with protection IEDs as devices under test (DUT)

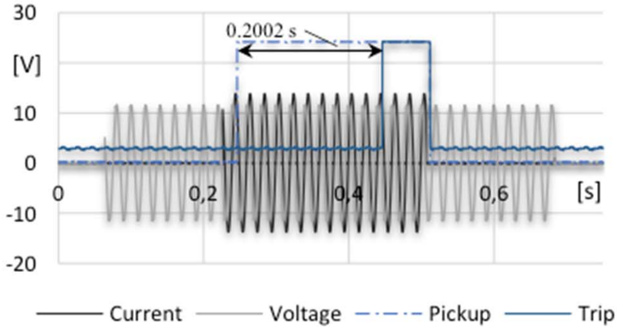


Figure 7: Example of IEC 60255-121 compliant type test step

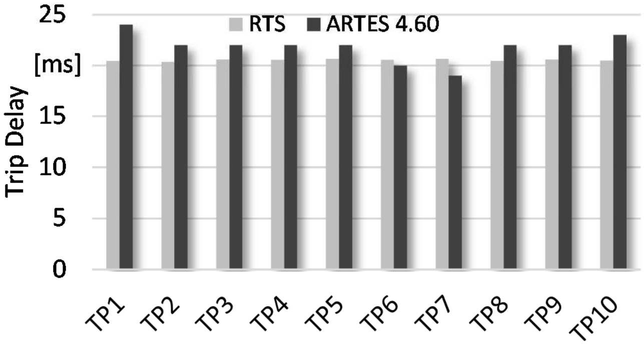


Figure 8: Performance of DRTS and conventional relay test system

3) *Real-Time Phasor Simulation for Distributed Smart Grid Control*

Functionalities such as fault detection and restoration, power flow control, loss optimization [18] and many others require a dedicated testbed. In the scope of the European demonstration project Grid4EU (German subproject) an HIL-simulator was developed for implementing and testing smart grid applications on real automation hardware [19].

In Figure 9 an overview of the simulator architecture is given. The overall structure is subdivided in the grid simulation domain and the hardware domain.

The grid simulation is software-based and takes place on a workstation PC. A network model implemented in MATLAB/Simulink® provides time-dependent behavior of loads and generators. Models of controllable devices are also included. The type of simulation is according to Figure 1b and implemented as a Phasor simulation. In the scope of Grid4EU, remote controlled circuit breakers act as controlling elements. All measurements and control signals are connected with an OPC server via data tags. On the other side a SCADA application PCU400 from ABB converts OPC data according to the DNP 3 protocol. This data emulates local signals for remote terminal units (ABB's RTU560 product).

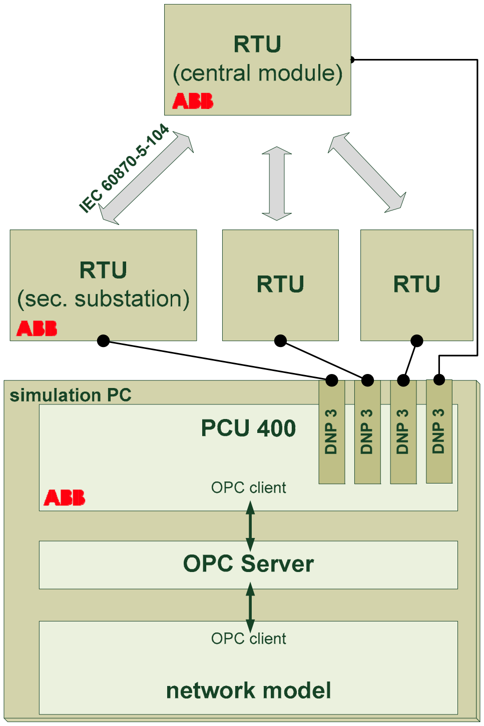


Figure 9: Architecture of the smart grid HIL-simulator

The hardware domain consists of the RTU local area network. Communication between single devices is implemented according to the IEC 60870-5-104 standard, which is also used in the real network. RTU modules exhibit a centralized hierarchy. Thereby, slave modules correspond to secondary substation RTUs and the central module implements algorithms, which require information from slave modules. Control algorithms of the central module generate switching sequences. These are transferred to the slave modules and afterwards transmitted to the network simulation via the OPC interface. Depending on the level of detail of the generation and load time series, different of simulation accelerations are applicable.

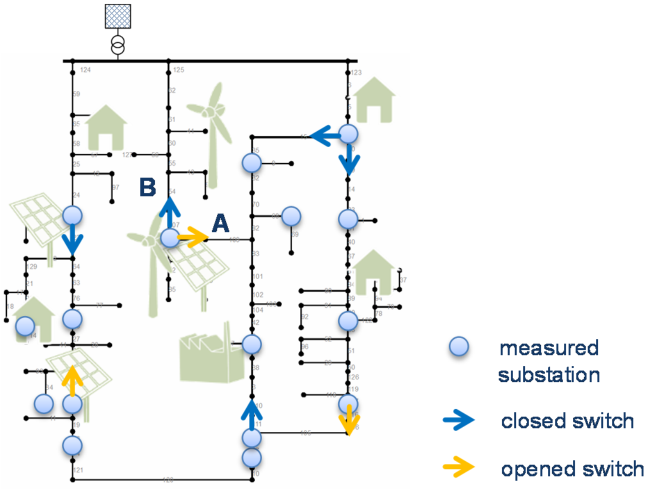


Figure 10: Grid4EU demonstration network model

The demonstration network (see Figure 10) includes 85 secondary substations, 16 of which and the primary substation are equipped with measurements. Eight switching devices are installed at six substations for network reconfiguration. The considered network is operated radially, so that three loops must remain opened.

In Figure 11, a process of network reconfiguration over time for the demonstration network is illustrated. After closing switch A and consequently opening switch B (see Figure 10), measured voltages remain in a lower range (Figure 11 red).

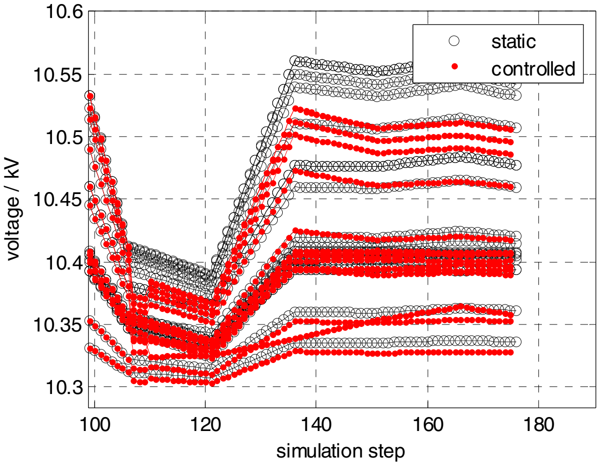


Figure 11: Voltage control in a MV-grid by network reconfiguration

A reference simulation, without applying control algorithms, shows uncontrolled voltage characteristics (Figure 11, black). The presented HIL-framework is suitable for scenarios where detailed dynamic modelling is not necessarily required. So, the RMS network simulation reflects voltage, current and power flow magnitudes over longer periods of time. This is well applicable for evaluating control algorithms in the distribution network domain.

4) Real-time Phasor Applications

Most of the time, voltage stability studies or computation of currents in the feeder do not need advanced EMT simulations. Dynamic phasor simulation tools, also known as transient stability (TS) programs or TS analysis (TSA) programs, provide accurate enough results for this type of application.[23] presents a project to supervise and optimize the Electrical Vehicle (EV) load in a distribution network. This work aims to develop smart EV recharging infrastructure that allows limiting environmental and financial impact by avoiding EVs charging during peak hours, and coordinating with wind and photovoltaic power sources.

In a first stage, the MV network (illustrated in Figure 12) model has been run on the PowerFactory software developed by DIgSILENT. As this simulation software does not allow real-time operation, ePHASORsim, developed by Opal-RT [14], has been used to obtain a real-time simulation. An interface tool has been developed to translate a PowerfFactory simulation into an ePHASORsim simulation.

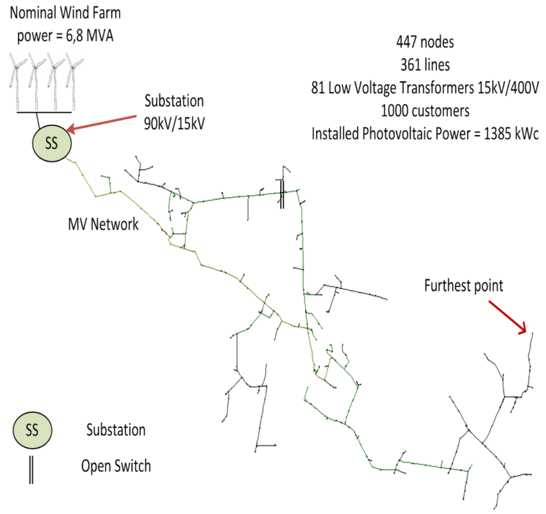


Figure 12: Medium Voltage network

A platform for distribution networks has been designed to test these algorithms. It consists of three main components: real time simulator with power amplifiers, customer loads emulators such as EV, and Advanced Metering Infrastructure. Figure 13 shows the complete system structure. First, two customers are extracted from the test network to recreate the test bench using: smart meters, charging station and batteries emulators. Second, the voltage signal at the meter connection points is reconstructed using phasor / EMT (ElectroMagnetic Transient) block. A 50 Hz sinusoidal signal is applied to the power amplifiers. This allows the injection of a power signal to meters and connected loads. The current provided by power amplifiers is measured and then transmitted to the real-time simulator. As shown in Figure 13, the actual charging stations are driven by a GPRS signal sent by the ICT of the DSO (Geredis). This control signal is sent by TCIP/IP link. In so doing, the transmission of the signal between a SCADA and the charging station is very accurately taken into account.

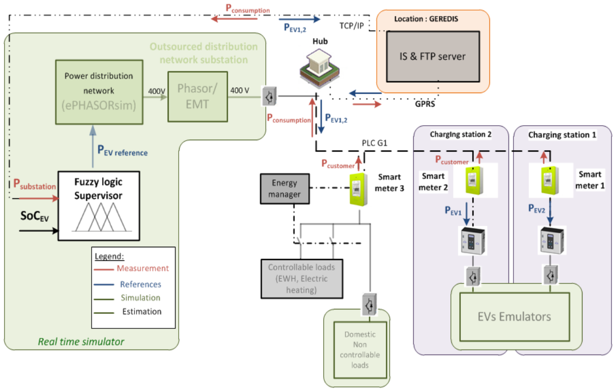


Figure 13: Test platform overview

As shown in Figure 14, supervision strategy adjusts the EVs charging to the wind power profile and the over voltages are slightly decreased.

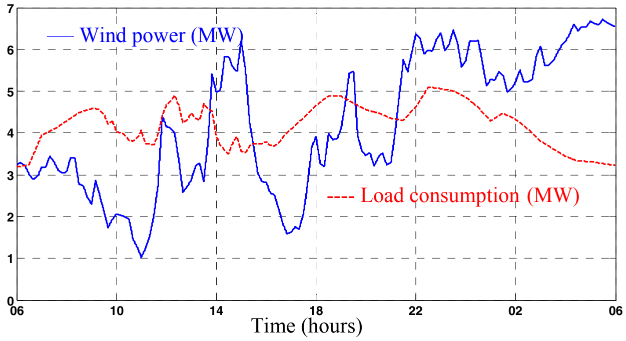


Figure 14: Wind power and load consumption profile

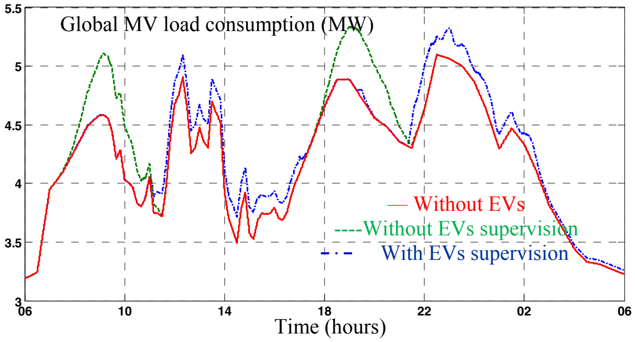


Figure 15: Global MV load consumption

5) *Hybrid Phasor/EMT Applications*

The use of both EMT and TS simulations are of interest in some cases [20][21]:

1) Lack of computational resources for the simulation of a large-scale power system. In this case, only the part of the power system which is of most interest (like FACTS or HVDC) is modeled in EMT, and the remainder in phasor domain.
2) The simulation of outages or blackouts with scale-bridging phenomena from electromechanical to EMTs is suitable for the combination of EMT and TS [22].
3) The need to use HIL with a system simulated in phasor mode [23].

However, the hybrid simulation is made possible by accepting reduced accuracy for fast transient events that could occur in the EMT model. In the TS simulation, high-frequency components are ignored. Thus, there is a loss of information on electrical signals between the EMT area and the phasor area, which is a compromise that needs to be accepted. This is in addition to the fact that phasor model and EMT model operate in multirate, typically 10 ms and 50 µs, respectively. Multirate that includes delays between the models may produce large error in some cases of fast transients. As presented in [24], [25] and [26], the accuracy of hybrid EMT-TS may look acceptable for an AC system; however, it is not always the case when an AC/DC system is considered. A solution is presented to improve the accuracy of the hybrid EMT-TS simulation with the AC/DC system. The solution is based on the integration of a frequency-dependent network equivalent (FDNE) at the interface between the EMT area and the phasor area. The role of the FDNE is to preserve the fast transient response of the power system by developing equivalents. The FDNE is obtained by fitting to the frequency response characteristic of the original network and it is modeled with a frequency-dependent admittance $[Y(f)]$ [24]. This allows taking into consideration the high-frequency component, which is ignored in the TSA solution.

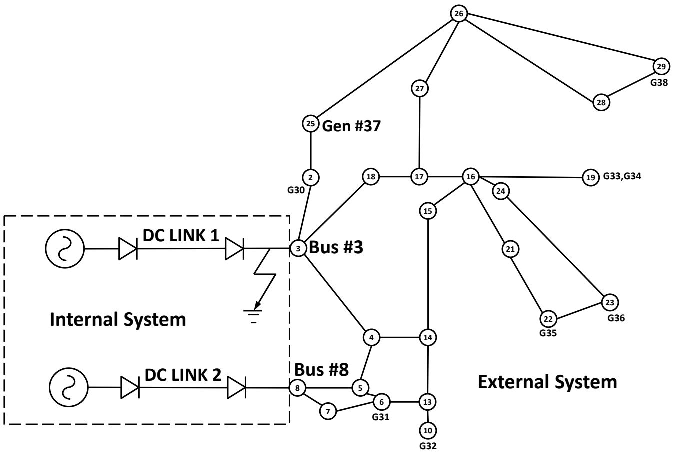


Figure 16: 39-bus New England AC system with two HVDC links [24]

In Figure 16, a hybrid RT simulation of the New-England 39-bus AC system with two HVDC links is presented. The full detailed model is used for HVDC link, while the AC power system is modeled in phasor. The results present the comparison between EMT full model, EMT-TSA, and EMT-FDNE-TSA. The improvement in accuracy due to the FDNE application for hybrid simulation is clear in Figure 17.

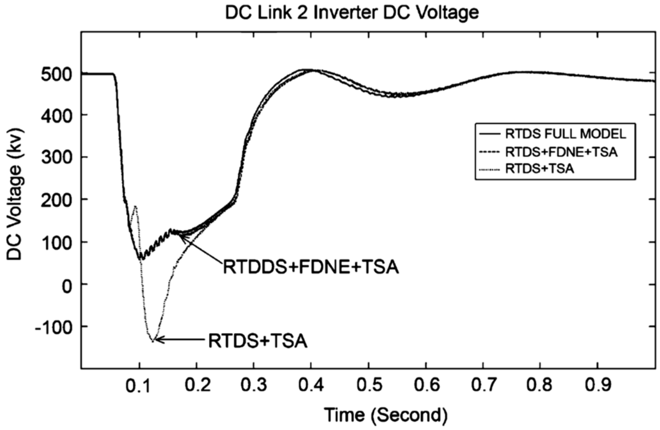


Figure 17: Comparison of the RTDS-FDNE-TSA and RTDS-TSA vs. Full RTDS simulation [24]

6) *FPGA Implementations and Applications*

The relatively large simulation time steps required by DRTSs relying on CPU-based solvers might be an obstacle to simulate high frequency phenomena, such as electromagnetic transients in power converters or electromagnetic propagation, in short transmission lines. In this respect, the recent literature has proposed a number of customized numerical solvers deployed in Field Programmable Gate Array (FPGA) hardware (e.g. [27][28][29]).

In regards to HIL-simulation of power electronics applications, FPGA-DRTSs provide several advantages over CPU-based ones. In particular, the parallel processing hardwired in FPGAs enables the implementation of specific numerical solvers that, in general, pipeline the solution of the problem resulting in a dramatic reduction of the sequencing of operations taking place in CPUs. In summary, FPGA-based real-time simulators provide higher sampling rate, higher frequency bandwidth and lower I/O latency [30].

However, FPGA-based real-time simulations suffer from two important limitations: first, the development of the numerical solver requires the use of Hardware Description Language (HDL), which limits the scalability with respect to complex models. Moreover, in FPGAs the matrix manipulations are limited and, as a consequence, frequent topology changes of the simulated circuit (e.g. switching in power electronics) requires special care. In this respect, the most straightforward method to represent topology-variable circuits in FPGA-DRTSs is the so-called Fixed Admittance Matrix Nodal Method (FAMNM) [31].

This method is based on an approximated switch model, which is represented by a capacitance when it is open and an inductance when it is closed. The inductance and capacitance are represented, in a discrete form, by a fixed conductance in parallel with a variable current source [32]. The conductance value is fixed irrespective to the switch state and the switch state only changes the value of the current source. As a consequence, regardless of the number of the switches and their states, such a model allows for obtaining a fixed nodal admittance matrix during switching transitions. However, this approximate model introduces artificial oscillations and errors in the simulation results (e.g. [33]).

Automated FPGA-DRTSs have been proposed to avoid the difficulties of the FPGAs programming (e.g. [34]). However, these industrial DRTSs exhibit difficulties in properly assessing the discrete-time switches' conductance to minimize the errors in the simulation results.

Recently, an automated FPGA-DRTS have been proposed in [29][35]. The developed DRTS platform is based on an industrial real-time embedded system (i.e., the National Instruments CompactRio Xilinx Kintex-7 platform) and has the following features: (i) it makes use of the Modified Nodal Analysis (MNA) method, (ii) it integrates the FAMNM together with an optimal selection of the switch conductance parameter proposed in [35], (iii) it accurately reproduces electromagnetic switching transients taking place in power electronic switching devices, and (iv) it is possible to reach extremely low integration time steps (in the order of hundreds of ns) and avoids the need to redesign the FPGA code.

Here, we provide an example of the performances of this specific FPGA-DRTS, assessed by making reference to a real test case composed of a three-phase inverter connected to an RL-load [29]. The assessment was done by comparing the FPGA-DRTS results with the offline benchmark simulation environment (i.e. EMTP-RV). Furthermore, a dedicated HIL-test has been carried out where the same external controller controls the FPGA-DRTS and a real inverter.

Figure 18 illustrates the comparison of the HIL simulation results and the measured waveforms for the three phase load currents in a half a period. Figure 19 shows the errors between the HIL simulation results and the measured waveforms. It can be observed that the HIL simulation results are concur with the measurements. It is worth mentioning that this comparison was performed in presence of the measurement noise and errors associated with the current measurement sensors.

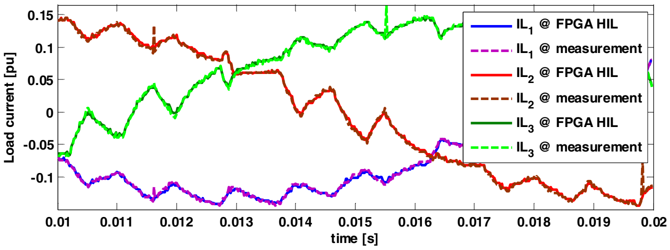


Figure 18: Comparison of the FPGA-based HIL test results with the measured results (three-phase load currents)

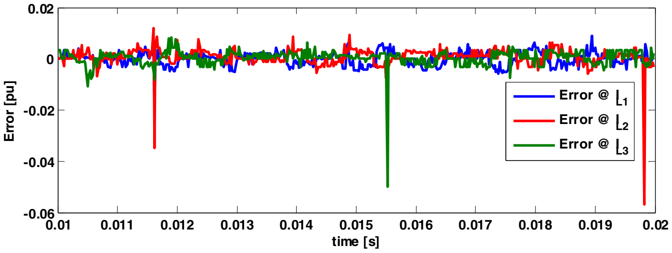


Figure 19: Error of the load currents in pu. (reference values of Figure 18)

In regards to the achieved integration time step, the simulation needs 6 FPGA ticks per time step, which, by considering the 40-MHz FPGA clock of the hardware platform, results in an integration time step of 150 ns.

7) *PHIL Applications*

PHIL is a specific application of Hardware in the Loop method when the test on the Hardware involved in the loop needs a significant amount of power. Many applications have been achieved for power electronic converters. Two types of PHIL may be distinguished depending on the power involved. For distribution type applications, it is possible to test the actual device in the loop. For transmission type applications, it is no longer possible. The converter under test must be scaled down. Both applications are now presented.

a) *Test of a photovoltaic inverter*

Figure 20 presents a PHIL setup for the test of a small PV inverter. The PV panel is simulated by power amplifier which mimics the I(V) nonlinear classical PV curves. One of the voltages simulated in real-time (u_{sim}) is sent to a Digital Analog Converter as a voltage reference for the power amplifier which applies this voltage to the actual PV inverter. The current in the PV inverter is measured and included in the real-time simulation as a current source (i_{sim}) (point 4). Since a closed loop is created, some stability issues may arise. [36] and [37] propose and analyze this problem in depth.

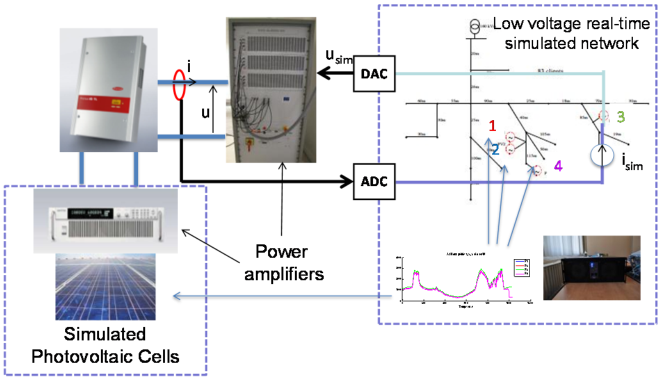


Figure 20: PV inverter under PHIL test

A small, low voltage distribution grid was simulated with 3 other PV plants connected to the grid (point 1, 2, 3). The aim of this experiment was to test Q = f(U) capability to manage the voltage in a distribution grid. Figure 21 represents the evolution of the active power, which is supposed to be the same, on the 4 converters.

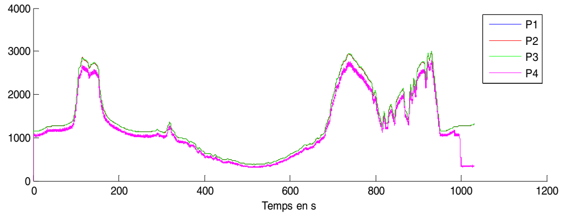
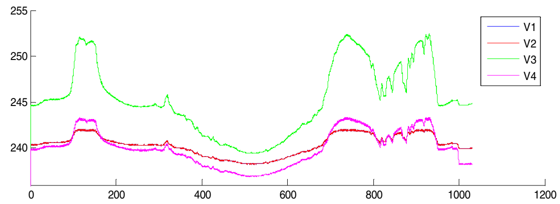


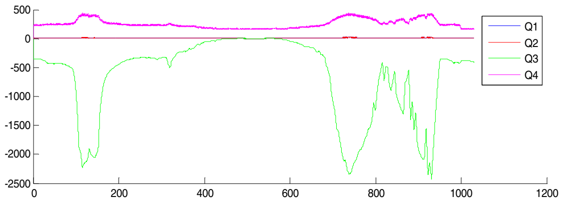
Figure 21: Active power on the 4 converters

A link between Figure 21 and Figure 22 a) shows the impact of the active power on the voltage in case of a low voltage grid where the R/X ratio is above 1. In the first case, the Q = f(U) control is applied only on the actual PV converter. As soon as the voltage increases, the inverter absorbs reactive power due to the Q = f(U) control. In Figure 23, the Q = f(U) control is also implemented on the PV converter connected to point 3. As expected, the 2nd inverter adjusts its reactive power to the voltage which induces a slight decrease on the voltage. No coupling is observed between both converters.

Many other applications were developed in PHIL. Among them, [38] presents a 500 kW PHIL PV converter test and [39] presents the development of MultiMegaWatt PHIL setup. In all these publications, only one device is tested. Some theoretical issues may arise if several devices are tested at the same time with some possible interaction as explained in [40].

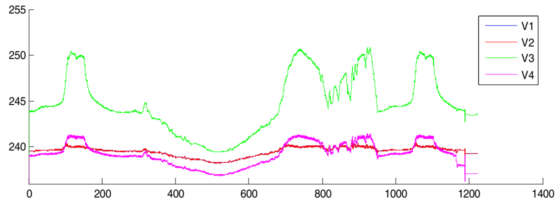


a) Voltage in point 1,2,3,4

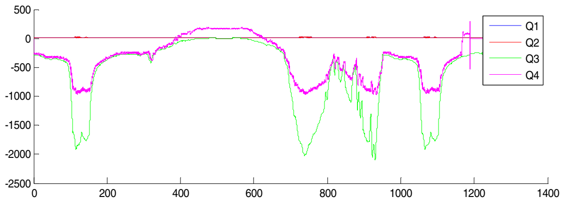


b) Reactive power in point 1,2,3,4

Figure 22: 1st case: Q= f(U) on the actual PV inverter



a) Voltage in point 1,2,3,4



b) Reactive power in point 1,2,3,4

Figure 23: 2nd case: Q= f(U) on the actual PV inverter and simulated inverter in point 3

b) Multi Terminal DC grid application

For transmission system application, it is not possible to test a device with its nominal operating point, since a huge power amplifier would be needed. A PHIL setup has been developed within Twenties European project to test the fault detection and management of the power in a 5 terminal DC grid as presented in Figure 24 [41].

A low voltage DC grid is composed of an actual set of different cables (15 km for the total length). The nominal DC voltage level has been fixed to 250V. The AC grid (Kundur system) and the wind farm are simulated in the real-time simulator. The 5 converters are the links between the AC and DC grid. Two of them are real 2 levels 3 kW VSC, 3 of them are real-time simulated 2 levels VSC. Their design is based on data from a 1000 MW converter station. The capacitor in per unit is the same as for high power application. Hence, this mock-up can be considered as a complex PHIL setup since 5 PHIL loops, one for each converter, may be involved. Since the power electronic converters are considered very scalable, this kind of mock up provides the ability to validate control algorithms devoted to DC grids in a very realistic environment.

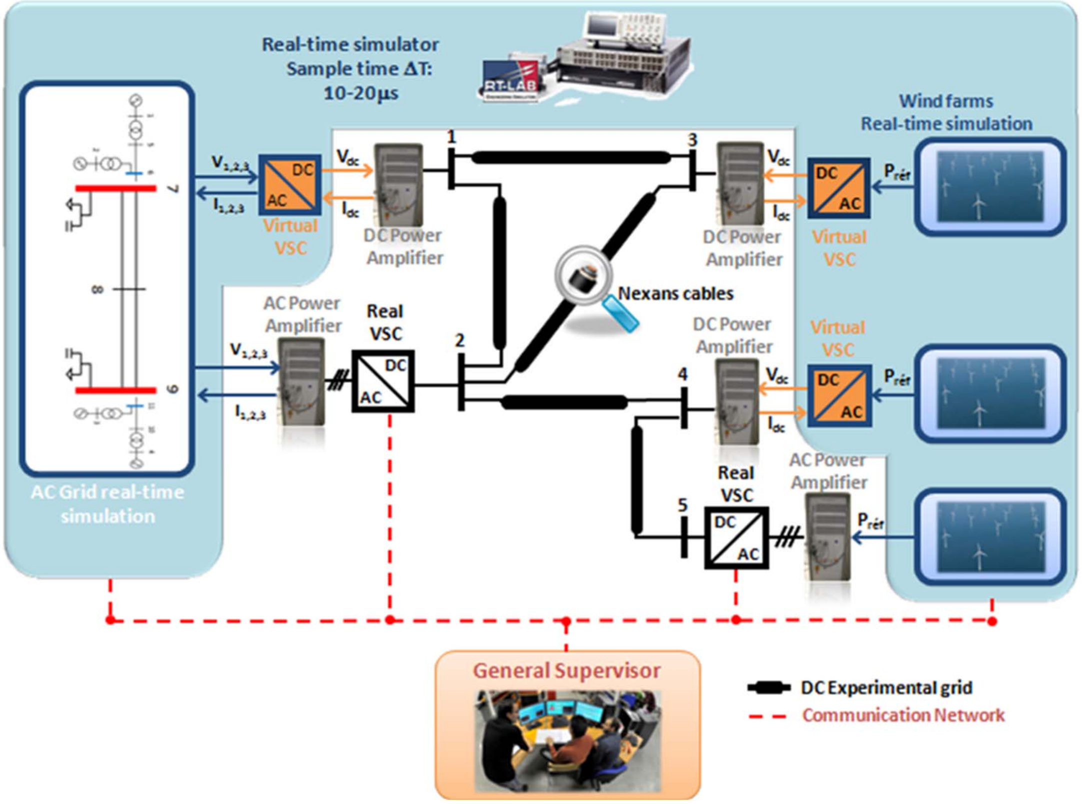


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Figure 24: Hybrid Multi Terminal DC grid

A SCADA system is used to control and monitor the mock-up. It was designed to act as a dispatching center and is able to monitor the states of each component, start stations from scratch, stop stations, change control mode of each converter station, send references to each station local controller and monitor and control AC simulated grids. The Master Terminal Unit (MTU) is equipped with PCVue software where a Human Machine Interface (HMI) has been developed. The communication between devices is through an Ethernet network. The OPC protocol was chosen to achieve the communication between multivendor devices: PCVue server, Beckhoff PLC, the OPAL-RT® simulator and other client computers. The latency of this SCADA system has been fixed to one second. Figure 25 summarizes the different information that is exchanged between the MTU and the Remote Terminal Units (RTUs).

The topology of the grid may be reconfigurable, including meshed grid and antenna connection. Though different types of experiments could be run on this equipment, this paper is focused on the power flow control.

Different control schemes of MTDC power grids have been proposed. A hierarchical control strategy inspirited by AC power system was implemented and tested. It is based on two levels: a local control level and a remote control level. In the local level, two control schemes using only local measurements have been implemented: master-Slave or droop modes. As droop modes have natural power-sharing capabilities, droop mode is more suitable for MTDC grids application than master-Slave mode. However, the main weakness of droop control is that power-flow dispatch is not perfectly controlled.

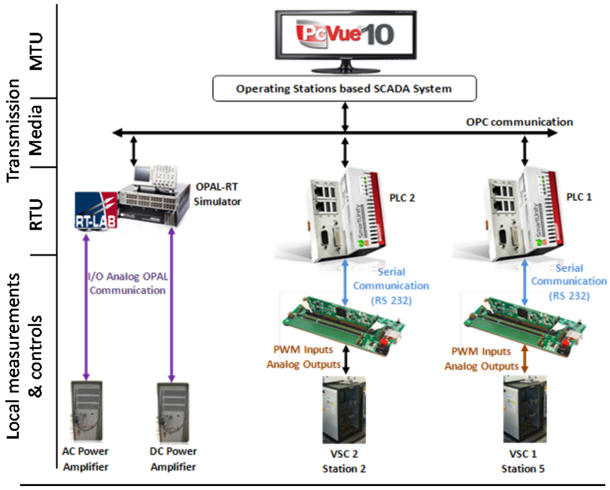


Figure 25: Mock-up communication scheme

A remote control level is then mandatory to improve power-flow dispatch. This remote control algorithm (managed generally by the system operator) aims for the optimization and safe operation of the whole system in normal operation. Several types of coordinated control strategies between the wind farm side Voltage Source Converters (VSCs) and the grid side VSCs have been tested on the proposed mock-up. The wind profile is given in Figure 26.

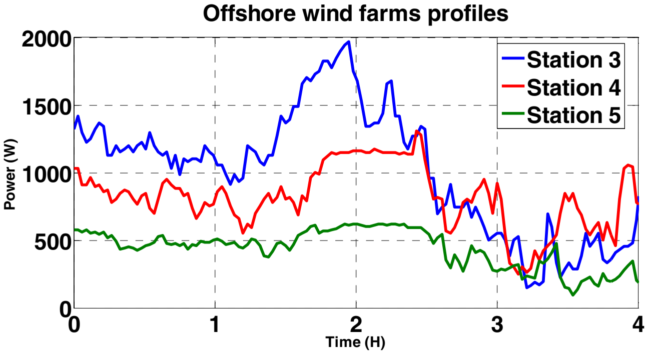
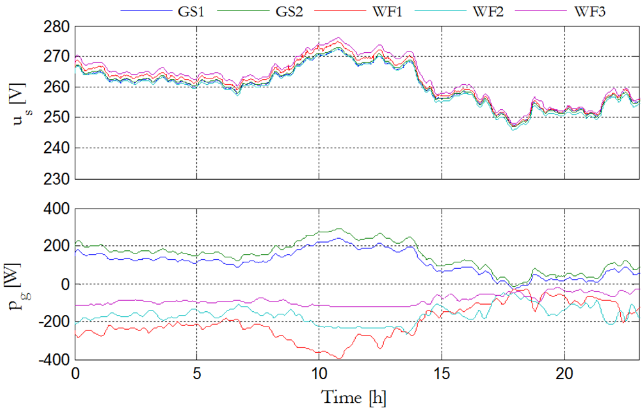
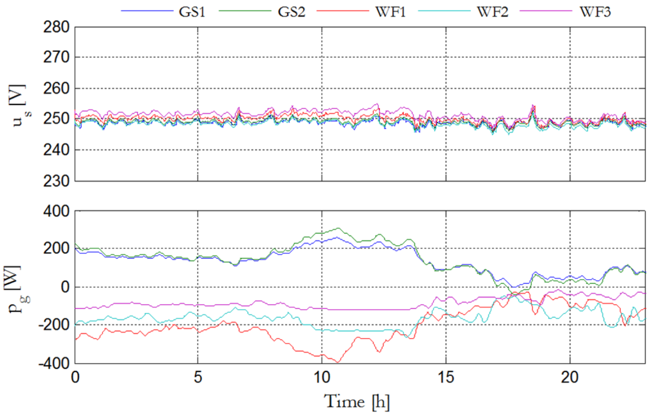


Figure 26: Wind profiles



a) Without coordination



b) With coordination

Figure 27: Voltages and powers in the DC grid

Figure 27 shows the voltage and power in five points of connection of the different converters. In Figure 27 a), no coordination is achieved between the different substations. The operating points are not modified and only the droop function is controlling the voltage. In Figure 27 b), a coordination is achieved. The operating point is modified in respect to the power on the wind turbines. It shows that the variations of voltage are much smaller than in the first case.

8) Smart Grids Lab for the validation of smart grid devices and control applications

Many future control applications require the interaction between local devices and the superior power system. The provision of ancillary services from distributed generators, loads and storages is currently one of the most famous examples for this.

The Smart Grids Lab, which is currently under construction at TU Dortmund University, provides a platform to simulate such interactions under realistic conditions. It is composed of real distribution grid components incorporated with a real-time simulator.

Either controllers can be tested as HIL-setups or power system devices can be incorporated using PHIL-configurations. The lab set-up consists of typical equipment of a low voltage grid: The grid is fed by a distribution voltage regulator transformer, which enables the voltage control in the low voltage grid. Several loads and feeders are connected such as PV-converters and battery storage systems. Adjustable cable emulators in between simulate the grid connection, strong and weak connections are reproducible. The reference voltage can be measured at several points in the grid. It helps to optimize its location. The behaviour of the superior grid and of the communication system is simulated on a real-time simulation system. Figure 28 gives an overview about the different applications of the Smart Grids Lab. HIL, as well as simulated models-in-the-loop simulations, are used to verify the integration of smart grid functionalities into the power system in consideration of power and communication network restrictions. This is used for analyzing systemic issues (like the provision of ancillary services from local devices) as well as single components in the overall system.

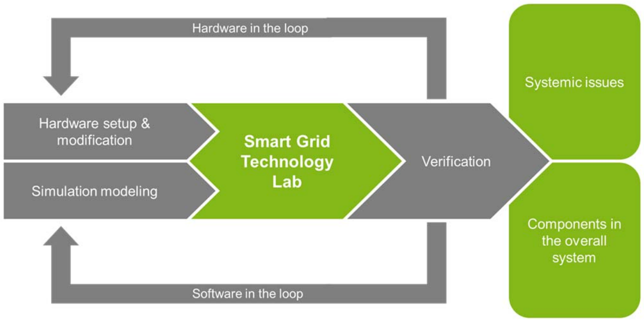


Figure 28: Applications of the Smart Grids Lab

Designing an Active Voltage Conditioner as a series device is an actual example for the verification of a single component with the Smart Grids Lab. Distributed infeeds such as PV-converters lead to voltage band violations in distribution grids.

The installation of new cables in parallel to the existing ones is possible but unfortunately an expensive solution. Another approach for solving the voltage problem is installation of an Active Voltage Conditioner. A rising voltage on a branch can be compensated by the unit before violating the voltage band restriction. One of the system properties is the transformer's impedance, which is dependent on regulator steps. So the active voltage control affects the line impedance as well, which has influence on other units of the grid, such as the anti-islanding unit of PV-converters which cannot cope with sudden steps of the line impedance in all cases. These and other reciprocal influences are investigated in the laboratory on real hardware devices and used to derive design criteria for the DUT.

III. CO-SIMULATION

A. *Introduction*

In this section, the principles and concepts of Co-Simulation are introduced. Based on that, implementations and applications are presented targeting research and development for smart grids.

Co-simulation allows for the reuse of models and enables experts from one domain and discipline to concentrate on their respective field of expertise. The modelling can be done on the subsystem level without having the wholescale interconnected system in mind. During the simulation, the subsystems will coordinate implicitly through the exchange of data [42]. There is an obvious trade-off between the independent development of subsystem models followed by their comfortable integration in co-simulation and performance-oriented simulation of complex systems or even systems of systems in a dedicated parallel or hybrid simulation [1]. Requirements for co-simulations are defined in [43].

B. *Principles and Concept of Co-Simulation*

When running two or more simulators in parallel within a co-simulation environment, there will always be the need to synchronize them. Providing functionalities to ensure a coordinated run of simulators is a central feature of co-simulation environments distinguishing between [44]:

- Continuous simulation: the simulator is able to produce output for every point in time. This is the case if the underlying modelling is done by using differential equations or if hardware emulators are used.
- Fixed step-size simulation: the simulator produces output for discrete points in time with a constant step size. This is commonly the case if physical systems are modelled that are too complex for an analytical solution so that numerical algorithms have to be used.
- Variable step-size simulation: the simulator produces output for discrete points in time, the interval between two steps may vary. The difference between variable step-size and an event driven simulation is that the step length has to be known at least one simulation step in advance.
- Event-driven simulation: the simulator produces output at discrete points in time with random intervals between the steps. This is the adequate modelling for systems that contain discrete dynamics like topology switching or sending or receiving data packets [1].

Systems described throughout this paper use different strategies to combine these types of simulators [44]. In the following, the underlying principle behind stepping between simulator executions of variable length and appropriate orchestration of information flows is presented. This *Anatomy of a Co-Simulation Step* is taken with permission from (https://mosaik.readthedocs.org/en/latest/scheduler.html):

1) *Anatomy of a Co-Simulation Step*

When starting a co-simulation composed of multiple simulators or solvers, all simulators are at their initial time 0. Keeping track of the time for multiple simulators throughout a co-simulation is done by a so called *scheduler*. When asking a simulator to execute its next step, the scheduler passes its current simulation time t_{now} to it. After its step, the simulator returns the time at which it wants to perform its next step (t_{next}). This time is then queued by the co-simulation scheduler. Thus, a simulator's step size doesn't need to be constant but can vary during the simulation. The data that a simulator computes during such a step is valid for the interval [t_{now}, t_{next}) as shown in Figure 29.

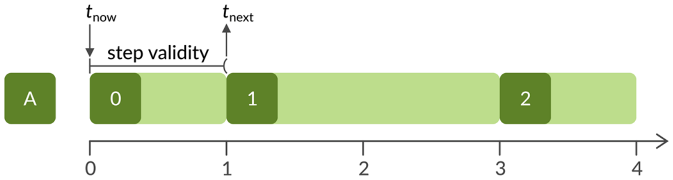


Figure 29: Schematic execution of a simulator A. t_{now}, t_{next} and the validity interval for its first step 0 are shown. The figure also illustrates that the step size of a simulator may vary during the simulation

2) *Synchronization and Data-Flows*

If there are data-flows between two simulators in a co-simulation (e.g. a simulated appliance connected to a power grid simulation), a simulator can only perform its step if all the necessary input data has been computed. Let's assume a basic example with two simulators A and B and a data-flow from A to B. Whenever B wants to execute a step from $t_{now(B)}$ the co-simulation scheduler determines which simulators provide the necessary input data for B (that has to be available and up-to-date in order for B to calculate a consistent next state or output). In this example the only necessary input comes from simulator A. Thus, in order to provide data for B, A needs to step far enough to produce data for $t_{now(B)}$, that means $t_{next(A)} > t_{now(B)}$ as illustrated in Figure 30 and Figure 32.

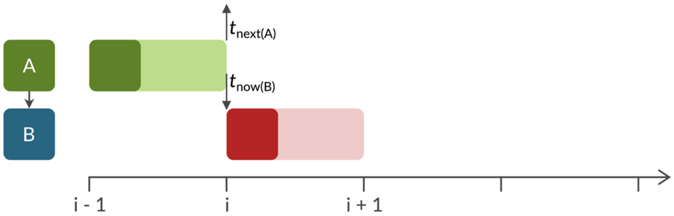


Figure 30: Simulator B cannot step because A has not progressed far enough ($t_{next(A)} \leq t_{now(B)}$)

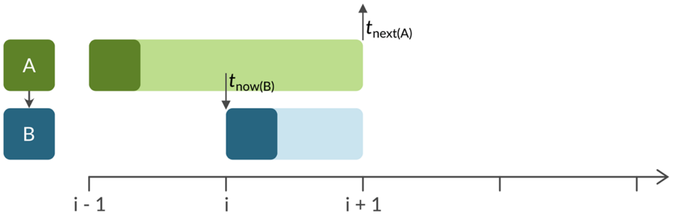


Figure 31: Simulator B can perform its next step, because A has progressed far enough ($t_{next(A)} > t_{now(B)}$)

If this condition is met for all simulators providing input for B, the scheduler (or orchestrator) collects all input data for B that is valid at $t_{now(B)}$ (i.e. a consistent snapshot of the global simulation state) and passes this data to B. Based upon this (and only this) data, B performs its next step $[t_{now(B)}, t_{next(B)})$. Figure 33 depicts this progression for the basic case of A and B having the same resolution or step-size.

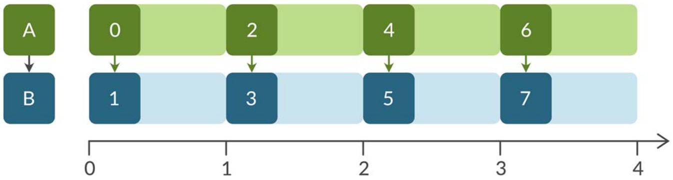


Figure 32: Simulator A and B have the same step size. The scheduler steps them in an alternating order starting with A, because it provides the necessary input data for B

If B has a larger step size than A, A would produce new data during the step length of B. B would use the input data that is valid at $t_{now(B)}$. This is depicted in Figure 33.

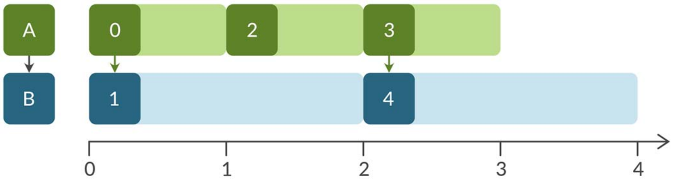


Figure 33: Simulator B has a larger step size than A and does not consume all data that is produced by A, because it gets the data the beginning of its step

On the other hand, if A has a larger step size than B, B would reuse the same data from A multiple times as long as it is valid (i.e. no new input is generated). This is depicted in Figure 34.

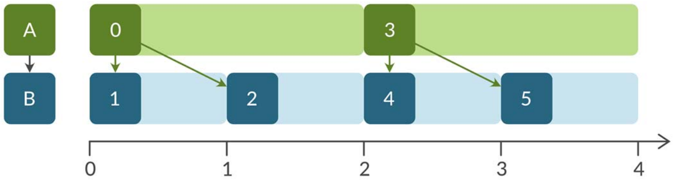


Figure 34: Simulator A has a larger step size than B and B reuses the same data multiple times.

Combinations of the latter two examples are the common in heterogeneous (large-scale) co-simulation setups of multiple simulators with variable step-size and resolution. Figure 35 illustrates a co-simulation setup with 5 simulators running on different (in this example fixed) step-sizes. Here, Δt denotes the individual step-size.

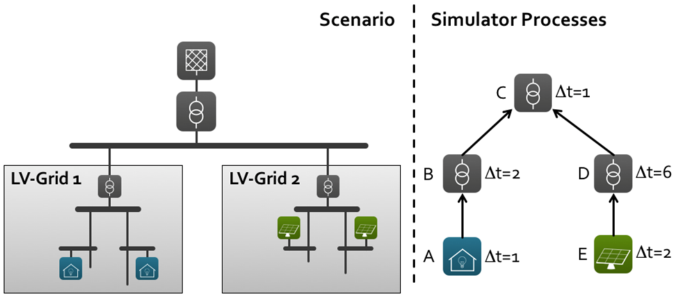


Figure 35: Co-simulation setup with 5 simulators running on different step-sizes

Figure 36 depicts the resulting schedule according to which the simulators are stepped and executed. For efficiency reasons intermediate executions of models whose export is not used may be skipped (dashed simulator executions in the figure). Following Figure 36, a complete cycle is completed once the simulator with the largest step-size is executed (simulator B).

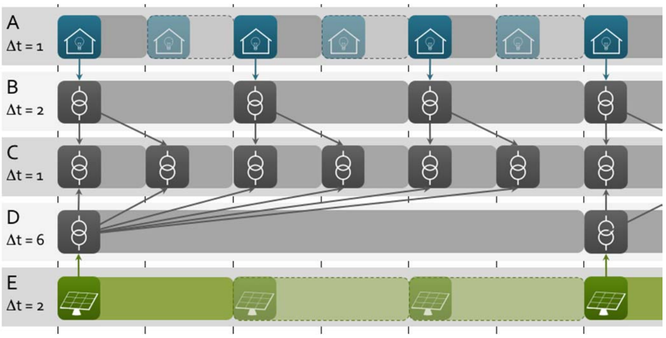


Figure 36 : Illustration of the resulting execution schedule

3) *Implementation Aspects*

Notably, there are several conceptual approaches to co-simulation. Recent trends have shown an increasing application of specified simulation frameworks which define standardized APIs for combining different simulators. Here, the IEEE Standard 1516-2000 (*High Level Architecture* (HLA)) [45] and IEEE 1516-2010 (*HLA Evolved*) [46] specify a standard for co-simulations. An HLA-based co-simulation (called a *Federation*) consists of different simulators (*Federates*) whose interactions are managed by a central administrating instance, the *Run Time Infrastructure* (RTI). Most importantly, the RTI provides mechanisms for a consistent object and time management. The standard specifies the framework and its terminology, rules for the federation and the individual federates, as well as object models and interfaces. Co-simulation development in conformity to the HLA standard provides the advantages that

(i) by design the approach enables distributed execution of the federates, (ii) RTIs (and hence time and object management mechanisms) are commercially available and (iii) some simulators already provide HLA-compatible interfaces.

However, for other simulators the respective interfaces and mechanisms have to be implemented in line with the requirements of the standard which can require significant effort or might even be impossible for some simulators. Besides HLA there have been additional specifications and frameworks for developing well-structured combined simulations, such as the *Functional Mock-Up Interface* (FMI) [47] and *Mosaik* [48].

The FMI approaches the problem of combining simulations by defining abstract functions and common interfaces for each simulation component, with more than 50 different simulation packages being conform to the FMI standard. Mosaik is a Python-based open-source co-simulation framework for coupling domain-specific simulators and to manage the joint simulation in a discrete event-based manner. Mosaik (https://mosaik.offis.de) is an Open-Source Smart Grid co-simulation framework [49][50]. By providing easy to use model interfaces in many programming and modelling languages, it allows to reuse and combine existing simulation models and simulators to create large-scale Smart Grid scenarios; that means thousands of simulated entities distributed over multiple simulator processes.

Beyond such specified frameworks managing the time synchronization and interactions of different simulators, other approaches apply an ad-hoc coupling, with interfaces between the simulators being directly implemented within the simulators themselves. This can increase the computational efficiency (e.g. as there is no overhead for a middleware), and no consideration of specified standards is required. For this, ad-hoc coupling is prominent in practice but issues such as extension of the co-simulation by additional simulators, scalability and long-term reuse of implementations can be achieved more easily by use of a specified framework such as HLA.

C. Implementations and Applications of Co-Simulators

In current research, various types of simulations have been linked with traditional power system simulators, such as standalone monitoring, protection and control applications simulations, market simulations, multi-physics simulations (e.g. to include heating), as well as ICT-system simulations. Among these, joint power and ICT-system simulation approaches have been a major driver for advancing co-simulations because they are critical for simulating and understanding novel smart grids and they pose particularly high challenges to the engineering due to

- high requirements on time synchronization because of the fundamentally different simulation types, with power system simulation being based on discrete time steps and ICT-system simulations being based on discrete events,
- high temporal solution as the processes in the ICT-domain frequently occur in the range of milliseconds and microseconds, and hence their effects is most relevant for simulating power system dynamics (in contrast to, e.g. stationary load flow calculations),
- and the resulting high computational complexity and need for scalability, in particular for evaluating large systems (e.g. for analyzing wide-area monitoring, protection and control (WAMPAC) systems) and for detailed models (e.g. for models considering both wide-area as well as local processes down to the bay-level).

For this, the focus is mainly set on co-simulations of power and ICT-system simulators in the following. As selected applications, these approaches enable to analyze the effect of ICT-processes and events in the ICT-system (e.g. latencies, communication link failures or cyber attacks) on the reliability and performance of smart grid applications or to analyze the adequacy of present or planned ICT-infrastructures for satisfying the requirements of smart grid applications.

1) Overview on Co-Simulator Implementations

In recent research, various co-simulation concepts and implementations have been proposed and published. Interfacing power and ICT simulations in a co-simulation was pioneered by the *Electrical Power and Communication Synchronizing Simulator* (EPOCHS) [51], which is based on HLA (IEEE 1516-2000). Here, PSCAD/EMTDC is used for EMT simulations and PSLF for RMS simulations of the power system, which are coupled with NS-2 as a communication network simulator. The focus of this work has been on simulating agent-based protection and control systems. The *Integrated Co-Simulation of Power and ICT systems for Real-time Evaluation* (INSPIRE) [52] was developed applying the more recent HLA Evolved standard (IEEE 1516-2010). Here, DIgSILENT PowerFactory is used for simulating the power system and OPNET-Modeller for simulating the ICT domain. The focus was on analyzing ICT-based protection and control systems in smart grids as well as on evaluating the performance and reliability of ICT infrastructures and protocols for the power system. INSPIRE considers IEC 61850 and IEEE C37.118 and has been designed with a generic architecture, which enables integration of additional applications and/or simulators implemented in C++, JAVA, GNU R or MATLAB [53]. Both EPOCHS and INSPIRE use a time-stepped synchronization based on HLA time management services, whereas INSPIRE applies dynamic synchronization points. Besides HLA, FMI has also been used for co-simulations in a specified simulation framework as in [54] and [55].

Among the ad-hoc coupling approaches, the *Global Event-Driven Co-Simulation Framework* (GECO) [56] belongs to the most advanced solutions. GECO interfaces PSLF (power system) with NS-2 (communication network) that uses a global event scheduler and global event queue for time synchronization. The focus was set on analysing PMU-based WAMPAC systems and cyber security of smart grid applications [57]-[58]. Also, the *Toolkit for Hybrid Modelling of Electrical power systems* (THYME) [59] enables the simulation of power systems as well as protection and control systems and communication networks in a discrete-event based manner. THYME is a publicly available module of *A*

Discrete EVent System simulator (ADEVS) [60] (based on the Discrete Event System Specification (DEVS) [61]), which can be interfaced with communication network simulators such as NS-2 and OMNET++ [62]-[63]. Further co-simulation approaches include VPNET (interfacing the Virtual Test Bed (VTB) for simulation of power and control systems with OPNET Modeller by a central coordinating entity for time synchronization and data exchange) [64]-[65], PowerNet (interfacing Modelica with NS-2) [66] and Greenbench (interfacing PSCAD and OPNET) [67]. Most of the afore mentioned approaches focus on analyzing the interactions of power and ICT domains to generally understand the interdependencies, performance drivers and vulnerabilities of smart grids and respective applications, which frequently do not require execution of the co-simulation in real-time. However, there are also co-simulation approaches that provide real-time capabilities, such as GridSim [68], which interfaces Powertech TSAT for time-domain simulation of the power system and GridStat, as well as [69] interfacing OPAL-RT with OPNET/SITL for real-time and HIL-simulations of WAMPAC applications.

For potential users of available co-simulation concepts, a structured decision-making for a suitable tool that takes the user's requirements into consideration is likely of interest, which has been addressed for the case of power and ICT co-simulations in [65].

2) *Smart Energy Simulation and Automation Lab*

The Smart Energy Simulation and Automation (SESA) Lab run by the OFFIS Institute for Information Technology and the University of Oldenburg in Germany follows a generic co-simulation approach. Even though it relies on a DRTS-platform, the system itself is not used directly for HIL-setups but rather for coupling of real-time dynamic hardware (emulated or physical components with high resolution phenomena range) with non-real-time systems that simulate discretized coarse-grained models and systems (Figure 37). In order for a dynamic higher-resolution component (physical hardware or emulation) to interact and exchange information with a more coarse-grained – yet potentially more extensive – simulated environment the SESA-Lab provides three layers of communication.

First, it is possible to interact with one another using the analog inputs/outputs provided by the DRTS. Second, components may interact via a real-time communication bus, simulating the communication (e.g. within a substation or between closely interconnected field devices). Third, components may communicate via a flexible communication layer that is modelled and co-simulated itself by a communication network simulator.

The latter may be configured to mimic communication with higher latency and limited bandwidth like long distance cellular mobile communication or protocol-specific communication dynamics (e.g. Modbus or IEC 60870-5-104). A schematic illustration is given in Figure 39.

Figure 37: A setup with multiple IEDs connected to the DRTS/Co-Simulator in the SESA-Lab

The primary use case of such a setup is the testing and analysis of IEDs that measure physical information (currents, voltages, phasors) locally but – in the scope of many smart grid concepts – communicate with one another via various forms of digital protocols (non-real-time or real-time) in order to coordinate a shared reaction (e.g. the optimally distribution of set points or the shifting of flexible loads) [70]. Additionally, the SESA-Lab may be used more generally to integrate, functionally combine and scale up models of various quality, precision, and model representation to multi-domain energy systems.

This flexibility facilitates the investigation of dynamic high-precision phenomena in a large-scale Smart Grid scenario of realistic and relevant size and scope. Next to a realistic representation of ICT-infrastructures and its aspects (communication system, protocols, SCADA system integration) the integrated assessment of such a co-simulation system's uncertainty (i.e. how large is the error in a multi-scale, multi-rate system of various individual model uncertainties orchestrated to perform one integrated simulation) is a major research topic for the SESA-Lab [71][72][73].

IV. CONCLUSIONS

This paper has presented many different applications with various ways of using real-time simulation or co-simulation. The first sets of applications presented the original way of using real-time simulation: Hydro-Quebec transmission system real-time simulation showed that it is possible to simulate very large grids with parallel processing whereas the second example explained the possible tests for protection devices as HIL-application. For the protection tests the DRTS provides real-time input data on real voltage and current level from flexible test scenarios. In comparison to traditional protection testing, automated test procedures can be implemented.

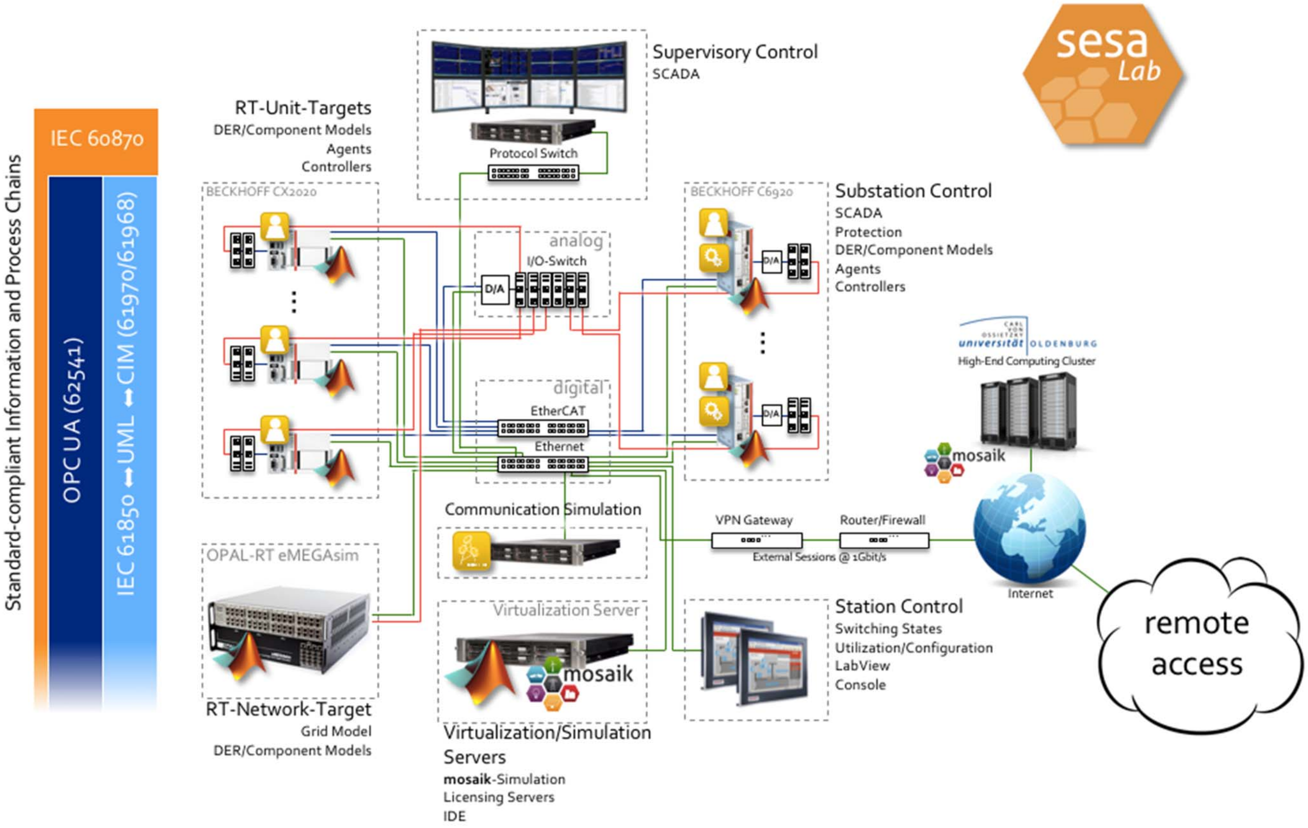


Figure 38: Interconnection scheme of the SESA-Lab showing the three communication layers

In the Grid4EU example, which performs HIL-tests for smart grid applications, no dedicated real-time simulator was used, since the computation of the grid was implemented as Phasor simulation within the conventional Matlab environment. This solution may be used when the time constraints are not too high for the specific application to be tested. For the same type of application, a dedicated real-time phasor simulator was used for managing the charging of batteries for electrical vehicles.

A connection between EMT and phasor simulation may be needed in case a power electronic converter is involved. Extra high speed real-time simulation was presented when a very accurate switching model for a power converter is studied. In this case, FPGA are well fitted but the implementation of the model is not an easy task and the Fixed Admittance Nodal Matrix Method reveals some limitations. For MMC applications, dedicated models are still useful but may need an expert in FPGA to develop such applications. Two types of PHIL applications were presented, depending on the power of the actual device tested. The most powerful PHIL applications can reach several MW, which requires a very powerful high bandwidth amplifier. It is still not sufficient for transmission applications. In such cases, a scale coefficient must be applied.

Even if real-time simulation is already achieving many applications, many other challenges are still to come. One such challenge is the connection between EMT and TSA application. Even if an example was presented, many improvements are still possible. Some studies have already been achieved for offline simulations where some iterative methods may be needed. They must be developed in the specific real-time conditions where the number of iterations is limited. The gateway between offline and real-time simulation is still to be improved. In some applications, the same software may be used, which can help avoid any problem of conversion between both simulation models. Most of the time, this conversion is still needed, which may induce some issues when the model is in between environments that are not exactly the same. The PHIL theory is still to be improved in terms of stability.

In the second part of the paper, co-simulation setups for real-time and non-real applications were introduced. Especially for smart-grid-applications, the simultaneous or integrated simulation of power system and ICT is crucial to test new developments before installing them in the real world.

In conclusion, a wide range of co-simulation solutions have already been proposed in recent research, which enables a joint simulation of various power system simulators, ICT simulators, separate control and protection application simulations, as well as additional external simulations. The SESA-lab was presented as a leading implementation of real-time co-simulations.

Notably, the required mathematical concepts for realizing concise co-simulations, as well as adequate software architectures and standards, are available. The major remaining challenges, however, are (i) structured performance evaluations and benchmarking of the different proposed solutions, (ii) improving the computational performance and scalability of the co-simulations for enabling their application in large-scale systems, and (iii) improving the reuse and enhancement of already elaborated works in this field,(e.g., by increasing compliance with standards). Further, the broader application of co-simulations in industrial applications is desirable for advancing the field of software development due to its crucial role for understanding smart grids (e.g., for avoiding guess work and simplifications with regard to ICT processes) when developing and testing protection and control applications for the power system

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