The What, Where and Why of Real-Time Simulation

J. Bélanger, *Member, IEEE*, P. Venne, *Student Member, IEEE*, and J.-N. Paquin, *Member, IEEE*

***Abstract*-- Simulation tools have been widely used for the design and improvement of electrical systems since the mid-twentieth century. The evolution of simulation tools has progressed in step with the evolution of computing technologies. In recent years, computing technologies have improved dramatically in performance and become widely available at a steadily decreasing cost. Consequently, simulation tools have also seen dramatic performance gains and steady cost decreases. Researchers and engineers now have access to affordable, high performance simulation tools that were previously too cost-prohibitive, except for the largest manufacturers and utilities. This paper introduces the role and advantages of using real-time simulation by answering three fundamental questions: what is real-time simulation; why is it needed and where does it best fit. The recent evolution of real-time simulators is summarized. The importance of model validation, mixed use of real-time and offline modes of simulation and test coverage in complex systems is discussed.**

***Index Terms*—accelerated simulation, hardware-in-the-loop (HIL), model-based design (MBD), power system simulation, rapid control prototyping (RCP), real-time simulation, software-in-the-loop (SIL).**

I. Nomenclature

COTS	Commercial off-the-shelf
DG	Distributed Generation
DSP	Digital Signal Processor
EMT	Electromagnetic Transients
FACTS	Flexible AC Transmission System
FPGA	Field-programmable Gate Array
HIL	Hardware-in-the-Loop
HVDC	High Voltage Direct Current
IGBT	Insulated-gate Bipolar Transistor
I/O	Inputs and Outputs
MBD	Model-based Design
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RCP	Rapid Control Prototyping
SIL	Software-in-the-Loop
TNA	Transient Network Analyzer

II. Introduction

SIMULATORS have been used extensively in the planning and design of electrical systems for decades. From the layout of transmission lines in large scale power systems to the optimization of motor drives in transportation, simulation has played a critical role in the successful development of a large number of applications.

For the last three decades, the evolution of simulation tools has been driven by the rapid evolution of computing technologies. As computer technologies have decreased in cost and increased in performance, the capability of simulation tools to solve increasingly complex problems in less time has improved. In addition, the cost of digital simulators has also steadily decreased, making them available to a larger number of users for a wider variety of applications.

The objective of this paper is to provide an introduction to real-time digital simulators, with a focus on Electromagnetic Transients (EMT), power systems modeling & simulation, and control prototyping techniques. First, real-time simulation is defined. An overview of the evolution of real-time simulators is then presented. Two other essential questions are then answered. Why is real-time simulation needed? Where does real-time simulation fit best? Finally, this paper concludes with discussion of the importance of model validation, the mixed use of real-time & offline simulation and test coverage in complex systems.

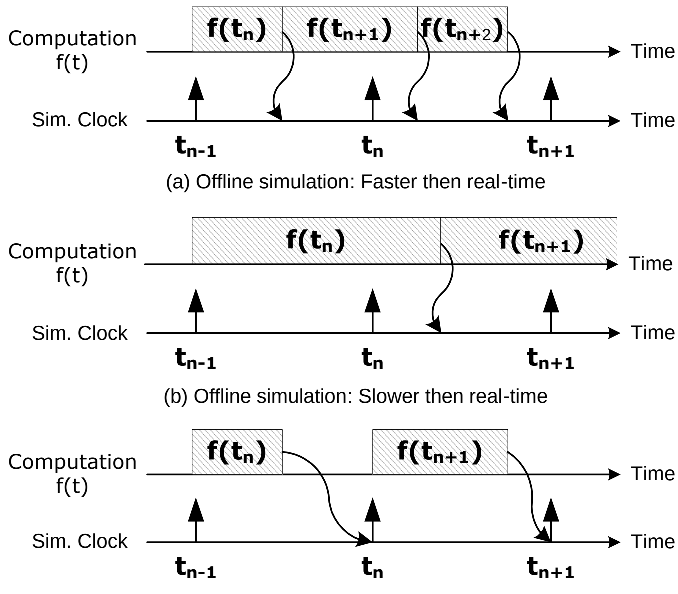
III. What is real-time simulation?

A. Time Runs Out and Real-Time Prevails

A simulation is a representation of the operation or features of a system through the use or operation of another [1]. For the types of digital simulation discussed in this paper, it is assumed a simulation with discrete-time and constant step duration is performed. During discrete-time simulation, time moves forward in steps of equal duration. This is commonly known as fixed time-step simulation [2]. It is important to note that other solving techniques exist that use variable time-steps. Such techniques are used for solving high frequency dynamics and non-linear systems, but are unsuitable for real-time simulation [3]. Accordingly, they are not covered in this paper.

To solve mathematical functions and equations at a given time-step, each variable or system state is solved successively as a function of variables and states at the end of the preceeding time-step. During a discrete-time simulation, the amount of real time required to compute all equations and functions representing a system during a given time-step may be shorter or longer than the duration of the simulation time-step. Figure 1 a) and Figure 1 b) represent these two possibilities. In a), the computing time is shorter than a fixed

J. Bélanger, P. Venne and J.-N. Paquin are with Opal-RT Technologies, 1751 Richardson, suite 2525, Montréal, QC H3K 1G6 CANADA (e-mail: {jean.belanger, philippe.venne, jean-nicolas.paquin}@opal-rt.com)

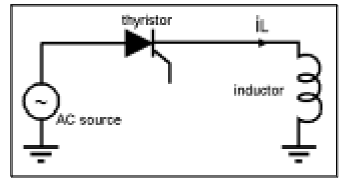


(a) Offline simulation: Faster then real-time

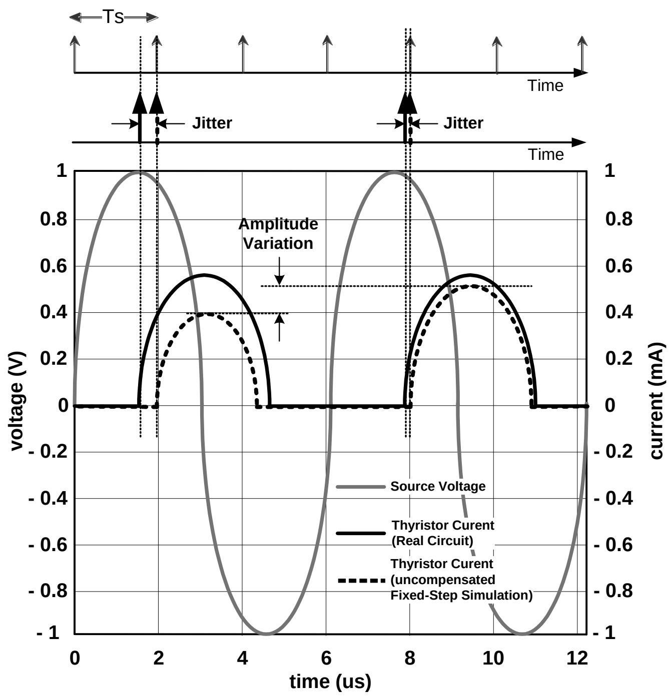
(b) Offline simulation: Slower then real-time

(c) Real-time simulation: Synchronized

Figure 1: Real-Time Simulation Requisites and Other Simulation Techniques



(a) Thyristor Converter Circuit



(b) Thyristor Converter Voltages

Figure 2: Timing Problem in a Thyristor Converter

time-step (also referred to as accelerated simulation) while in b), the computing time is longer. These two situations are referred to as offline simulation. In both cases, the moment at which a result becomes available is irrelevent. Typically, when performing offline simulation, the objective is to obtain results as fast as possible. The system solving speed depends on available computation power and the system's mathematical model complexity.

Conversely, during real-time simulation, the accuracy of computations not only depends upon precise dynamic representation of the system, but also on the length of time used to produce results [4]. Figure 1 c) illustrates the chronological principle of real-time simulation. For a real-time simulation to be valid, the real-time simulator used must accurately produce the internal variables and outputs of the simulation within the same length of time that its physical counterpart would. In fact, the time required to compute the solution at a given time-step must be shorter than the wall-clock duration of the time-step. This permits the real-time simulator to perform all operations necessary to make a real-time simulation relevant, including driving inputs and outputs (I/O) to and from externally connected devices (further discussed in section III. D. and E.). For a given time-step, any idle-time preceding or following simulator operations is lost; as opposed to accelerated simulation, where idle time is used to compute the equations at the next time-step. In such a case, the simulator waits until the clock ticks to the next time-step. However, if simulator operations are not all achieved within the required fixed time-step, the real-time simulation is considered erroneous. This is commonly known as an "overrun".

Based on these basic definitions, it can be concluded that a real-time simulator is performing as expected if the equations and states of the simulated system are solved accurately, with an acceptable resemblance to its physical counterpart, without the occurence of overruns.

B. Timing and Constraints

As previously discussed, real-time digital simulation is based on discrete time-steps where the simulator solves model equations successively. Proper time-step duration must be determined to accurately represent system frequency response up to the fastest transient of interest. Simulation results can be validated when the simulator achieves real-time without overruns.

For each time-step, the simulator executes the same series of tasks: 1) read inputs and generate outputs 2) solve model equations 3) exchange results with other simulation nodes 4) wait for the start of the next step. A simplified explanation of this routine suggests that the state(s) of any externally connected device is/are sampled once at the beginning of each simulation time-step. Consequently, the state(s) of the simulated system is/are communicated to external devices only once per time-step. As introduced in section III. A. , if not all real-time simulation timing conditions are met, overruns occur and discrepancies between the simulator results and its physical counterpart's responses are observed.

The required use of a discrete-time-step solver is an inherent constraint of today's real-time simulators, and can be a major limitation when simulating non-linear systems, such as HVDC, FACTS, active filters or drives. Because of the nature of discrete-time-step solvers, the occurence of non-linear events in a real-time simulation, such as transistor switching, can cause numerical instability. Solving methods to prevent this problem have been proposed in [5] and [6], but they cannot be used during real-time simulation. Achieving real-time is one thing, but achieving it synchronously is another. With non-linear systems, such as the simple rectifier circuit illustrated in Figure 2, there is no guarantee that switching events will occur (or should be simulated) at a discrete time instance. Furthermore, multiple events can occur during a single time-step, and without proper handling the simulator may only be aware of the last one. Recently, real-time simulator manufacturers have proposed solutions to timing and stability problems. Proposed solutions generally known as discrete-time compensation techniques usually involve time-stamping and interpolation algorithms. State-of-the-art real-time simulators take advantage of advanced I/O cards running at sampling rates considerably faster than fixed-step simulation [7], [8]. The I/O card acquires data faster than the simulation, and can read state changes in between simulation steps. Then, at the beginning of the next time-step, the I/O card not only passes state information on to the simulator, but also timing information as to when the state change occurred. The simulator can then compensate for the timing error.

Figure 2 illustrates a classical case of simulation error caused by the late firing of a thyristor in a converter circuit. In this example, a thyristor is triggered at a 90-degree angle with respect to the AC voltage source positive zero-crossing. As soon as the thyristor is triggered, current begins to flow through it. The resulting load current obtained through uncompensated real-time simulation (dotted line) is represented with a degree of error in comparison to the current flowing through the real circuit (plain black line). This is because the event at 90 electrical degrees does not occur synchronously to the simulator fixed-time-step. Thus, the thyristor gate signal is only taken into account at the beginning of the next time-step. This phenomenon is commonly known as "jitter". When jitter occurs in a discrete-time simulation, sub-synchronous or uncharacteristic harmonics (amplitude variations) may be visible in resulting waveforms. In this case, variations are evident in the thyristor current.

Finally, the use of multiple simulation tools and different time-step durations during real-time simulation can cause problems. When multiple tools are integrated in the same simulation environment, a method known as co-simulation, data transfer between tools can present challenges since synchronization and data validity must be maintained [9]. Furthermore, in multi-rate simulations, where parts of a model are simulated at different rates (with different time-step durations), result accuracy and simulation stability are also issues [10]. For example, multi-rate simulation may be used to simulate a thermal system with slow dynamics alongside an electrical system with fast dynamics [11]. Multi-rate simulation and co-simulation environments, where multiple tolls are used side by side, is an active research topic.

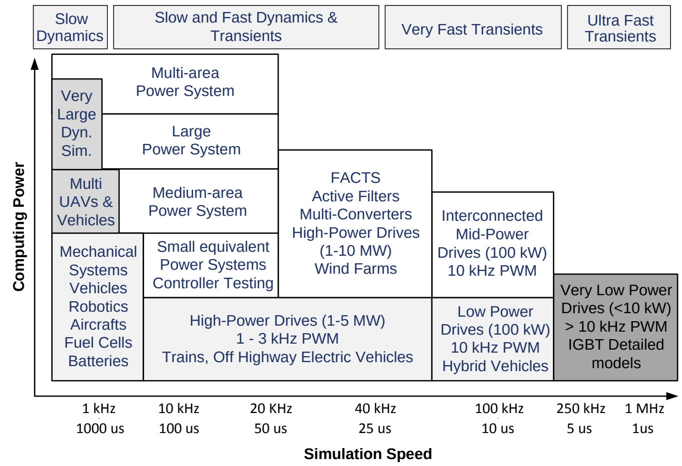


Figure 3: Simulation Time-step by Application

C. Choosing the Right Simulator for the Right Time-step

The first challenge faced by simulation specialists is to select a real-time simulator that will meet their needs. Simulator capabilities, size and cost are determined by a number of criteria, including 1) the frequency of the highest transients to be simulated, which in turn dictates minimum time-step, and 2) the complexity or the size of the system to simulate, which along with the time-step duration, dictates the computing power required. The number of I/O channels required to interface the simulator with physical controllers or other hardware is also critically important, affecting the total performance and cost of the simulator.

Figure 3 outlines typical time-step and computing power requirements for a variety of applications. The left side of the chart illustrates mechanical systems with slow dynamics that generally require a simulation time-step between 1 and 10 milliseconds, according to the rule of thumb that the simulation step should be smaller than 5% to 10 % of the smallest time constant of the system. A smaller time-step may be required to maintain numerical stability in stiff systems. When friction phenomena are present, simulation time-steps as low as 100 microseconds to 500 microseconds may be required.

It is a common practice with EMT simulators to use a simulation time-step of 30 to 50 microseconds to provide acceptable results for transients up to 2 kHz. Because greater precision can be achieved with smaller time-steps, simulation of EMT phenomena with frequency content up to 10 kHz typically require a simulation time-step of approximately 10 microseconds.

Accurately simulating fast-switching power electronic devices requires the use of very small time-steps to solve system equations [12]. Offline simulation is widely used, but is time consuming if no precision compromise is made on models (i.e. the use of average models). Power

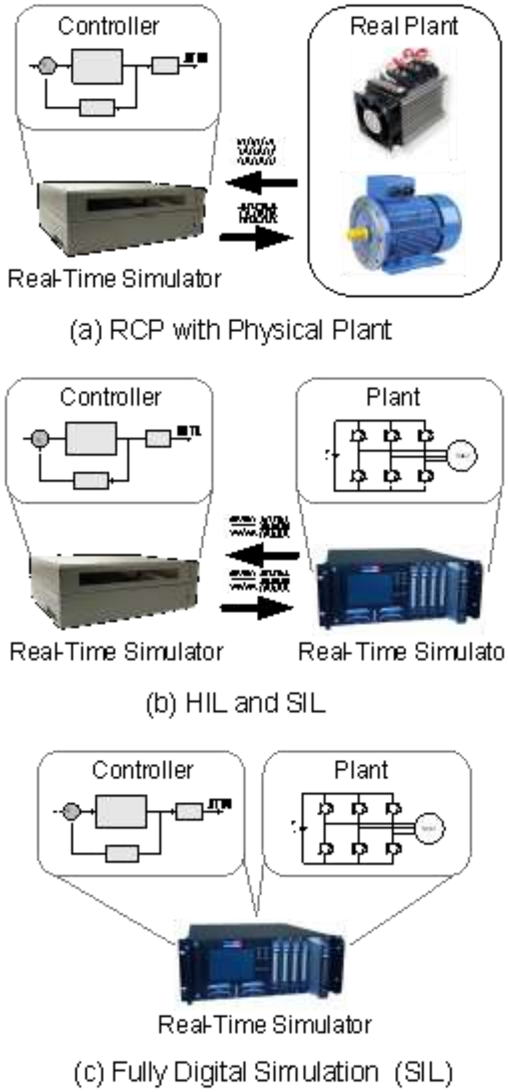


Figure 4: Applications Categories

electronic converters with a higher PWM carrier frequency in the range of 10 kHz, such as those used in low-power converters, require time-steps of less than 250 nanoseconds without interpolation, or 10 microseconds with an interpolation technique. AC circuits with higher resonance frequency and very short lines, as expected in low-voltage distribution circuits and electric rail power feeding systems, may require time-steps below 20 microseconds. Tests that use practical system configurations and parameters are necessary to determine minimum time-step size and computing power required to achieve the desired time-step.

State-of-the-art digital real-time simulators can exhibit jitter and overhead of less than 1microsecond, thereby enabling time-step values as low as 10 microseconds, leaving plenty of processing resources available for computation of the model. This means that simulation time-steps can be reduced to a considerably low value, as necessary, to increase precision or to prevent numerical instability.

Regardless of the simulator used, both numerical solver performance and the bandwidth of interest are considerations when selecting the right time-step. The standard approach for selecting a suitable fixed step-size for models with increasing complexity is a time-domain comparison of waveforms for repeated runs with different step-sizes.

D. Rapid Control Prototyping

Real-time simulators are typically used in three different application categories, as illustrated in Figure 4. In RCP applications (Figure 4 (a)), a plant controller is implemented using a real-time simulator and is connected to a physical plant. RCP offers many advantages over implementing an actual controller prototype. A controller prototype developed using a real-time simulator is more flexible, faster to implement and easier to debug. The controller prototype can be tuned on the fly or completely modified with just a few mouse clicks. In addition, since every internal controller state is available, an RCP can be debugged faster without having to take its cover off.

E. Hardware-in-the-Loop

For HIL applications, a physical controller is connected to a virtual plant executed on a real-time simulator, instead of to a physical plant. Figure 4 (b) illustrates a small variation to HIL; an implementation of a controller using RCP is connected to a virtual plant via HIL. In addition to the advantages of RCP, HIL allows for early testing of controllers when physical test benches are not available. Virtual plants also usually cost less and are more constant. This allows for more repeatable results and provides for testing conditions that are unavailable on real hardware, such as extreme events testing.

F. Software in the loop

SIL represents the third logical step beyond the combination of RCP and HIL. With a powerful enough simulator, both controller and plant can be simulated in real-time in the same simulator. SIL has the advantage over RCP and HIL that no inputs and outputs are used, thereby preserving signal integrity. In addition, since both the controller and plant models run on the same simulator, timing with the outside world is no longer critical; it can be slower or faster than real-time with no impact on the validity of results, making SIL ideal for a class of simulation called accelerated simulation. In accelerated mode, a simulation runs faster than real-time, allowing for a large number of tests to be performed in a short period. For this reason, SIL is well suited for statistical testing such as Monte-Carlo simulations. SIL can also run slower than real-time. In this case, if the real-time simulator lacks computing power to reach real-time, a simulation can still be run at a fraction of real-time, usually faster than on a desktop computer.

IV. EVOLUTION OF REAL-TIME SIMULATORS

Simulator technology has evolved from physical/analogue simulators (HVDC simulators &TNAs) for EMT and protection & control studies, to hybrid TNA/Analogue/Digital simulators capable of studying EMT behavior [13], to fully digital real-time simulators, as illustrated in Figure 5.

Physical simulators served their purpose well. However, they were very large, expensive and required highly skilled

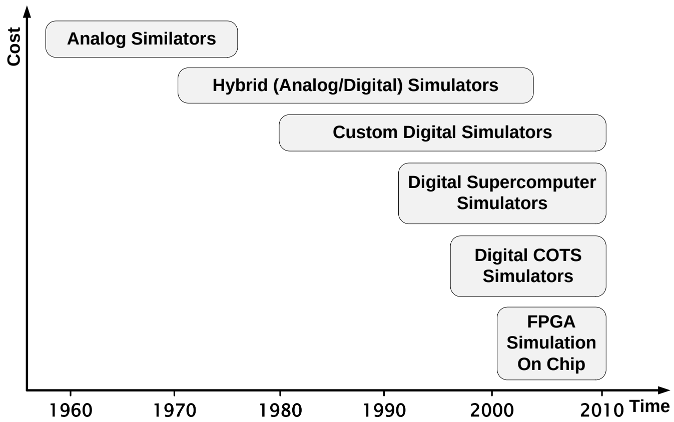


Figure 5: Evolution of Real-Time Simulation Technologies

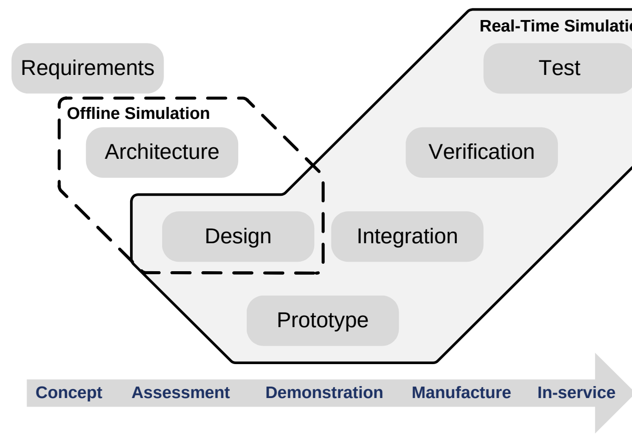


Figure 6: Model-based Design Workflow

technical teams to handle the tedious jobs of setting up networks and maintaining extensive inventories of complex equipment. With the development of microprocessor and floating-point DSP technologies, physical simulators have been gradually replaced with fully digital real-time simulators.

DSP-based real-time simulators developed using proprietary technology, and used primarily for HIL studies, were the first of the new breed of digital simulator to become commercially available [14]. However, the limitations of using proprietary hardware were recognized quickly, leading to the development of commercial supercomputer-based simulators, such as HYPERSIM from Hydro-Quebec [15], which is no longer commercially available. Attempts have been made by universities and research organizations to develop fully digital real-time simulators using low-cost standard PC technology, in an effort to eliminate the high costs associated with the use of high-end supercomputers [16]. Such development was very difficult due to the lack of fast, low-cost inter-computer communication links. However, the advent of low-cost, readily available multi-core processors [17] (from INTEL and AMD) and related COTS computer components has directly addressed this issue, clearing the way for the development of much lower cost and easily scalable real-time simulators. In fact, today's low-cost computer boards equipped with eight processor cores provide greater performance than 24-CPU supercomputers that were available only 10 years ago. The availability of this low-cost, high performance processor technology has also reduced the need to cluster multiple PCs to conduct complex parallel simulation, thereby reducing dependence on sometimes-costly inter-computer communication technology.

COTS-based high-end real-time simulators equipped with multi-core processors have been used in aerospace, robotics, automotive and power electronic system design and testing for a number of years [18]. Recent advancements in multi-core processor technology means that such simulators are now available for the simulation of EMT expected in large-scale power grids, microgrids, wind farms and power systems installed in all-electric ships and aircraft. These simulators, operating under Windows, LINUX and standard real-time operating systems, have the potential to be compatible with a large number of commercially available power system analysis software tools, such as PSS/E, EMTP-RV and PSCAD, as well as multi-domain software tools such as SIMULINK and DYMOLA. The integration of multi-domain simulation tools with electrical simulators enables the analysis of interactions between electrical, power electronic, mechanical and fluid dynamic systems.

The latest trend in real-time simulation consists of exporting simulation models to FPGA [19]. This approach has many advantages. First, computation time within each time-step is almost independent of system size because of the parallel nature of FPGAs. Second, overruns cannot occur once the model is running and timing constrains are met. Last but most importantly, the simulation time-step can be very small, in the order of 250 nanoseconds. There are still limitations on model size since the number of gates is limited in FPGAs. However, this technique holds promise.

V. Why is Real-Time Simulation needed?

A. *Model-based Design*

MBD is a mathematical and graphical method of addressing problems associated with the design of complex systems [20]. MBD is a methodology based on a workflow known as the "V" diagram, as illustrated in Figure 6. It allows multiple engineers involved in a design and modelling project to use models to communicate knowledge of the system under development, in an efficient and organized manner [21]. Four basic steps are necessary in the process: 1) build the plant model; 2) analyze the plant model and synthetize a controller for it; 3) simulate the plant and controller together and 4) deploy the controller.

MBD offers many advantages. By using models, a common design environment is available to every engineer involved in creating a system from beginning to end. Indeed, the use of a common set of tools facilitates communication and data exchange. Reusing older designs is also easier since the design environment can remain homogeneous through different projects. In addition to MBD, graphical modeling tools, such as the SimPowerSystem toolbox for Simulink from The MathWorks [22], simplify the design task by reducing the complexity of models through the use of a hierarchical approach. Modeling techniques have also been employed in order to embed independent coded models inside the power systems simulation tool PSCAD/EMTDC [23].

Most commercial simulation tools provide an Automatic Code Generator that facilitates the transition from controller model to controller implementation. The added value of real-time simulation in MBD emerges from the use of an Automatic Code Generator [24], [25]. By using an Automatic Code Generator with a real-time simulator, an RCP can be implemented from a model with minimal effort. The prototype can then be used to accelerate integration and verification testing, something that cannot be done using offline simulation. The same holds true for HIL testing. By using an HIL test bench, test engineers become part of the design workflow earlier in the process, sometimes before an actual plant becomes available. For example, by using the HIL methodology, automotive test engineers can start early testing of a car controller before a physical test bench is available. Combining RCP and HIL, while using the MBD approach, has many advantages:

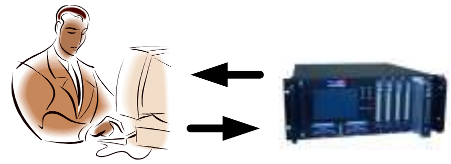
- Design issues can be discovered earlier in the process, enabling required tradeoffs to be determined and applied, thereby reducing development costs;
- Development cycle duration is reduced due to parallelization in the workflow;
- Testing costs can be reduced in the medium- to long-term since HIL test setups often cost less then physical setups and the real-time simulator employed can be typically used for multiple applications and projects ;
- Testing results are more repeatable since real-time simulator dynamics do not change through time the way physical systems do;
- Can replace risky or expensive tests using physical test benches;

B. Interaction with the Model

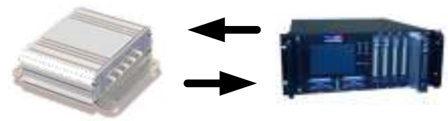
Figure 7 illustrates the advantages of model interaction. These interactions can be (a) with a system user, (b) with physical equipment or (c) with both at the same time.

When a user or physical equipment interacts with a real-time model, they can provide model inputs and get model outputs, as it would with a real plant. A model executed on a real-time simulator can also be modified online, which is not possible with a real plant. In addition, any model parameter can be read and updated continuously. For example, in a power plant simulation, the shaft inertia of a turbine can be modified during simulation to determine its effect on stability, something impossible on a real power plant.

Furthermore, with a real-time simulator, any model quantity is accessible during execution. For example, in a wind turbine application, the torque imposed on the generator from the gearbox is available, since it is a modeled quantity. In a real wind turbine, getting a precise torque value in real-time is near impossible due to the prohibitive cost of a torque meter.



(a) Interaction with a User



(b) Interaction with Equipment

(b) Interaction with a User and Equipment

Figure 7: Types of Simulator Interaction

Online model configuration and full data availability make previously unthinkable applications possible. For example, verifying if a controller can compensate for changes in plant dynamics caused by component aging.

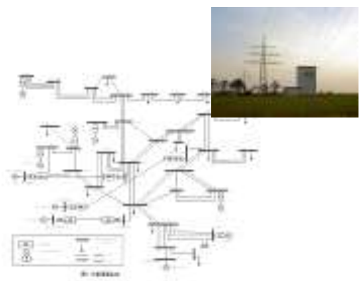
VI. Where Does it Fit Best?

A. Power Generation Applications

Testing of complex HVDC networks, SVCs, STATCOMs and FACTS device control systems, under steady state and transient operating conditions, is a mandatory practice during both the controller development phase and before final system commissioning [26], [27], [28]. Testing is performed in order to reduce risks associated with conducting tests on physical networks. HIL testing must be performed successfully with a prototype controller before a real controller is installed in the field. Thousands of systematic and random tests are typically required to test performance under normal and abnormal operating conditions. This testing can also detect instabilities caused by unwanted interactions between control functions and the power system, such as other FACTS devices that may interact with the system under test.

Protection & insulation coordination techniques for large power systems use statistical studies to deal with inherent random events, such as the electrical angle at which a breaker closes, or the point-on-wave at which a fault appears [29]. By testing multiple fault occurrences, measured quantities can be identified, recorded and stored in databases for later retrieval, analysis and study. While traditional off-line simulation software (e.g. ATP, EMTP) can be used to conduct statistical

(a) Multilevel VSC-Based STATCOM



(b) Large Power Systems

(c) Renewables Integration

Figure 8: Power Generation Applications

studies during the development of protection algorithms, once a hardware relay is built, further evaluation and development may require using a real time simulator. Typical studies include digital relay behavior evaluation in different power system operating conditions. Furthermore, relay action may influence the power system, increase distortions, and thus affect other relays. Because it is a two-way street, closed loop testing in real time is necessary for many system studies and for protection system development.

The integration of DG devices, including some microgrid applications, and renewable energy sources (RES), such as wind farms, is one of the primary challenges facing electrical engineers today [30], [31], as illustrated in Figure 8 (c). It requires in-depth analysis and the contributions of many engineers from different specialized fields. With the growing demand in the area, there is a need for engineering studies of the impact that the interconnection of DG and RES will have on specific grids. The fact that RES and DG are usually connected to the grid using power electronic converters is a challenge in itself. Accurately simulating fast-switching power electronic devices requires the use of very small time-steps to solve system equations. Moreover, synchronous generators, which are typically the main generation sources on grids, have a slow response to EMT. The simulation of fast-switching power electronic devices in combination with slow electromechanical components in an electrical network is challenging for large grid benchmark studies; even more so if proper computation resources are not available. Off-line simulation is widely used in the field but is time consuming, particularly if no precision compromise is made on models (i.e. the use of average models). By using real-time simulation, the overall stability and transient responses of the power system can be investigated in a timely matter, both before and after the integration of RES and DG,. Statistical studies can be performed to determine worst-case scenarios, optimize power system planning and mitigate the effect of the integration of these new energy sources.

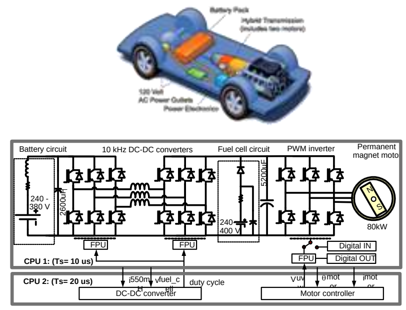


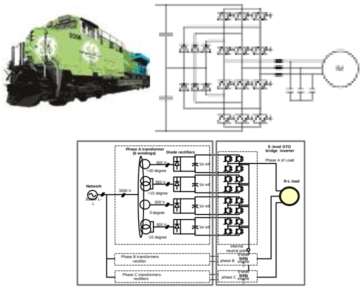
Figure 9: Automotive Applications

B. Automotive Applications

Hybrid electric vehicles built by companies like Toyota and Honda have become economically viable and widely available in recent years. Considerable research is also underway in the development of fuel cell hybrid electric vehicles, where the main energy source is hydrogen-based. Successful research & development of fuel cell hybrid electric vehicles requires state-of-the-art technology for design and testing. Lack of prior experience, expensive equipment and shorter developmental cycles are forcing researchers to use MBD techniques for development of control systems [32]. For this reason, thorough testing of traction subsystems is performed using HIL simulation [33], as illustrated by Figure 9. For example, a real-time simulation of a realistic fuel cell hybrid electric vehicle circuit, consisting of a fuel-cell, battery, DC-DC converter and permanent magnet motor drives, with a sufficient number of I/O for real controllers in HIL mode, can now be done with a time-step duration below 25 microseconds [34].

C. All-Electric Ships & Electric Train Networks

Today, the development and integration of controllers for electric train and All-Electric Ship applications is a more difficult task than ever before. Emergence of high-power switching devices has enabled the development of new solutions with improved controllability and efficiency. It has also increased the necessity for more stringent test and



(a) Electric Train

(b) All-electric Ship

Figure 10: Train and Ship Applications

integration capabilities since these new topologies come with less design experience on the part of system designers. To address this issue, real-time simulation can be a very useful tool to test, validate and integrate various subsystems of modern rail and marine vehicle devices [35], as illustrated by Figure 10. The requirements for rail/marine vehicle test and integration reaches several levels on the control hierarchy, from low-level power electronic converters used for propulsion and auxiliary systems to high-level supervisory controls.

The modular design and redundancies built into the power system of an All-Electric warship are critical in ensuring the ship's reliability and survivability during battle. For instance, auxiliary propulsion systems will dynamically replace the primary system in case of failure. This implies that the power system can be dynamically reconfigured, such as in zonal electric distribution systems (ZEDS) designed by the US Navy. Therefore, power management operations need to be highly efficient. Power quality issues must be kept to a minimum, and operational integrity must be as high as possible during transients caused by system reconfigurations or loss of modules. The design and integration of an All-Electric Ship's ZEDS is a challenge. It requires testing of the interactions between hundreds of interconnected power electronic subsystems, built by different manufacturers. Large analog test benches or the use of actual equipment during system commissioning is therefore required at different stages of the project. A real-time simulator can be used to perform HIL integration tests to evaluate the performance of some parts of these very complex systems, thereby reducing the cost, duration and risks related to the use of actual equipment

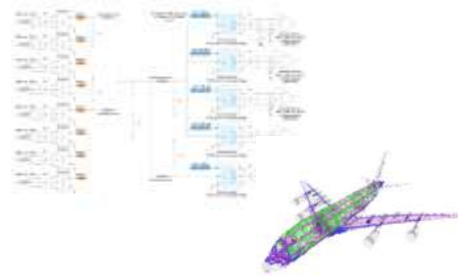


Figure 11: Aerospace Applications

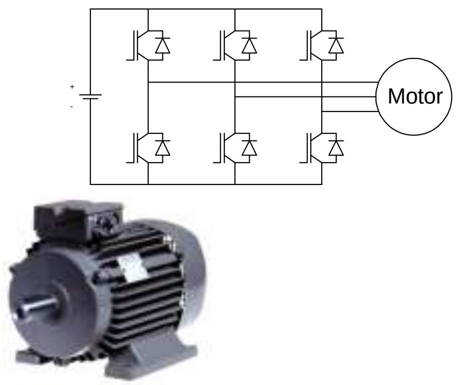


Figure 12: Smaller Scale Applications

to conduct integration tests [36].

D. Aerospace

While most aerospace applications do not need the extremely low time-steps required in power generation or automotive applications, repeatability and accuracy of simulation results is extremely critical for safety reasons. Accordingly, aircraft manufacturers must conform to stringent industry standards. Developed by the US-based Radio Technical Commission for Aeronautics (RTCA), the DO-178B standard establishes guidelines for avionics software quality and testing in real-world conditions [37]. DO-254 is a formal standard governing design of airborne electronic hardware [38].

The complex control systems found onboard today's aircraft are also developed and tested according to these standards. As a result, aerospace engineers need higher precision testing and simulation technologies that will ensure compliance. They must also meet the market's demands for innovative new products, built on time, to spec and within budget.

E. Electric Drive & Motor Development and Testing

A critical aspect in the deployment of motor drives is the early detection of defects in the design process. The later in the process that a problem is discovered, the greater the cost to fix it. Rapid prototyping of motor controllers is a methodology that enables the control engineer to quickly deploy control algorithms and find eventual problems. This is performed using an RCP connected in closed-loop with a physical prototype of the drive to be controlled, as illustrated in Figure

12. This methodology implies that the real motor drive is available at the RCP. Furthermore, this set-up requires a second drive (such as a DC motor drive) to be connected to the motor drive under test to emulate the mechanical load. While this is a complex setup, it has proven very effective in detecting problems earlier in the design process. In cases where a physical drive is not available, or where only costly prototypes are available, an HIL-simulated motor drive can be used during the RCP development stage. In such cases, the dynamometer, real IGBT converter and motor are replaced by a real-time virtual motor drive model. This approach has a number of advantages. For example, the simulated motor drive can be tested with borderline conditions that would otherwise damage a real motor. In addition, setup of the controlled-speed test bench is simplified since the virtual shaft speed is set by a single model signal, as opposed to using a real bench, where a second drive would need to be used to control the shaft speed [39].

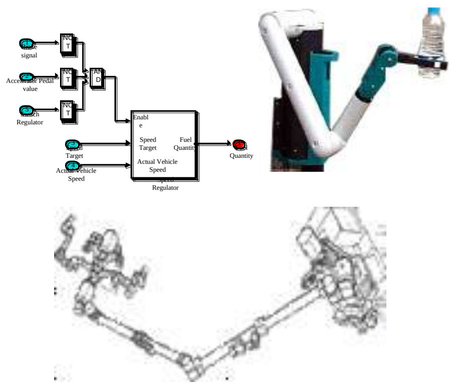


Figure 13: Mechatronic Applications

F. Mechatronics: Robotics & Industrial Automation

Mechatronic systems that integrate mechanical and electronic capabilities are at the heart of robotic and Industrial Automation applications. Such systems often integrate high-frequency drive technology and complex electrical and power electronic systems. Using real-time simulation for design & test helps ensure greater efficiency of systems deployed in large-scale manufacturing and for unique, but growing applications of robotics.

Figure 14: Education Applications

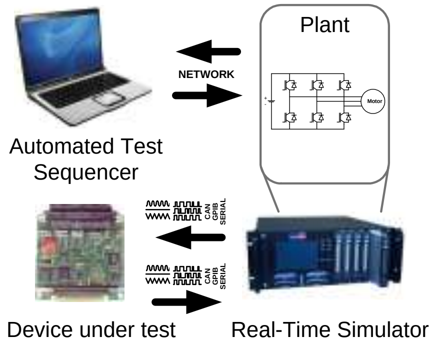
G. Education: University Research into Development

To keep pace with the current technological revolution, universities must change. New ways must be found to teach future engineers using a transdisciplinary approach; leveraging the possibilities offered by new tools that talented engineers are seeking, while providing them with practical experience that cultivate their creativity [40]. In this context, electronic circuit simulators such as CircuitLogix, based on PSpice, have been used as teaching aids for many years in electronics and control system classes. Their workflow is quite straightforward; build the circuit with the circuit editor tool, run the simulation and analyze the results. However, when it is necessary to study the effect of the variation of many parameters (oscillator frequency, duty cycle, discrete component values) this process can take a great deal of time [41]. In such situations, interactive simulation, based on a real-time simulator that enables model parameter changes on the fly, becomes a valuable teaching tool. With such a tool, changes to the model are instantly visible, providing students with the live feedback required for them to get a feel for how a system reacts to the applied changes, as illustrated in Figure 14.

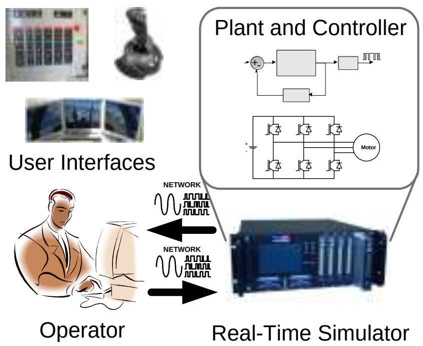
H. Emerging Applications

Real-time simulation is in use in two additional emerging applications. Since a real-time simulator can provide outputs and read inputs, it is an ideal tool for equipment commissioning and testing, as depicted in Figure 15 (a). Not only can it mimic a real plant, it can emulate other devices, play a recorded sequence of events and record a device under test response. Modern simulators can also provide simulated network connections such as CAN, GPIB and Ethernet. The application of real-time simulators to equipment commissioning and tests is common in the manufacturing of electronic control modules (ECMs). For this application, the use of real-time simulators saves test bench costs and reduces testing time.

Real-time simulation can also be used for operator and technician training, as illustrated in Figure 15 (b). While this application category is in an early growth stage, it offers great potential. For this category of application, both controller and plant are modeled in the same simulator using an SIL-like approach. The difference is that user interfaces are added in order to allow the operator to interact with the simulation in a user-friendly way. Interfaces such as control panels and joysticks manage user inputs, but also provide feedback to the user about the simulation state. The advantage of using a real-time simulator for training is that the user can get a feeling for the controller and plant that correctly represents the real system, without the delays and limitations commonly found in training environments based on pre-recorded scenarios.

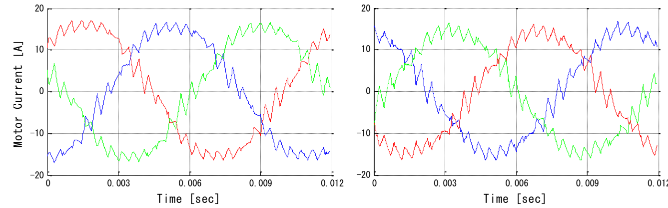


(a) Equipment Commissioning and Tests

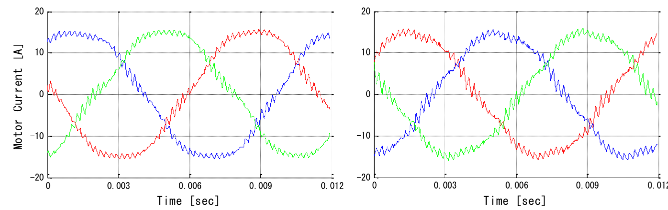


(b) Operator & Technician Training

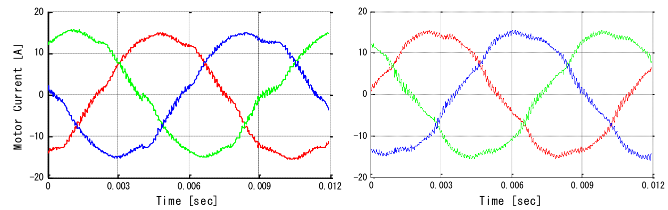
Figure 15: Emerging Applications



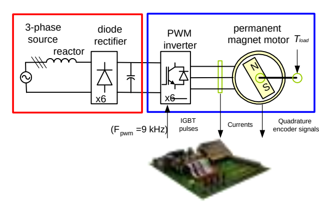
(a) HIL Simulation (left) and Physical System (right) at 2.25 kHz PWM



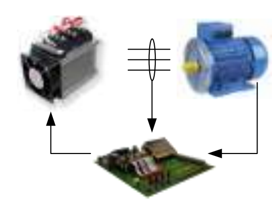
(b) HIL Simulation (left) and Physical System (right) at 4.5 kHz PWM



(c) HIL Simulation (left) and Physical System (right) at 9 kHz PWM



(d) HIL Simulation Setup



(e) Physical System Setup

Figure 16: Real-Time Simulation Validation

VII. Food for Thought

A. A Word on Validation

While the complexity of design projects has steadily increased, engineers face growing pressure to reduce development costs and time-to-market of new products. As a result, testing and validation of complex systems has become an important part of the design process. In the case of AC motor drives, engineers use the HIL methodology to connect a part of the system or its prototype to a real-time digital model of the remaining part of the system.

The most critical criterion in conducting a real-time digital simulation is how to obtain acceptable model accuracy with an achievable simulation time-step. This is an especially challenging task for simulation of fast-switching power electronics and motor drives. These non-linear systems need very small time-steps to achieve an acceptable degree of accuracy.

A basic question then emerges: How can one trust the validity of simulator results? To build trust in a simulation tool, a large number of validation tests must be performed using many different applications, configurations, time-steps and I/O cards. In the example of the AC motor drive, a validation test is performed against a physical test setup, as illustrated by Figure 16 (d) and (e).

In this setup, PWM signals from the controller are captured using an FPGA-based I/O card. By capturing PWM signals with an FPGA-based card, the times of rising and falling transitions are recorded and then forwarded to the IGBT model. To make use of transition times, it is necessary to use a special IGBT inverter model; in this case an RT-EVENTS time-stamped inverter model [8] that implements interpolation for fixed-step simulation of voltage source inverters and PWM generation units.

By using an FPGA-based I/O board to capture PWM gate signals, and a time-stamped, interpolated inverter model, it is possible to circumvent the jitter problem encountered when simulating switching converters at a large fixed time-step, and associated non-characteristic harmonics and anomalies. In addition, it is possible to take into account the effect of dead time, even if it is much smaller than the real-time simulation step.

For this experiment, the carrier frequency is set respectively to 2.25, 4.5, and 9.0 kHz; the effect of these frequencies on the oscillation of current waveforms is verified, as shown in Figure 16 (a), (b) and (c). The experiment parameters are: Motor speed = 1,800 r/min, Motor torque = 16.0 Nm, Dead Time = 4.2 µs. A comparison of the current of the HIL simulator and actual physical system shows they are very similar for all carrier frequencies [42].

B. Added Value of Mixing Offline and Real-Time Simulation

Simultaneous simulation of fast and long phenomena pushes the simulation tools used in the planning and operation of power systems to their limits. Indeed, such challenges are multi-disciplinary. Each specialized field may require the use of multiple design, prototyping and simulation tools. When considering power systems only, different tools may be used for load flow studies, stability analysis and EMT simulations. The transient response of an interconnected power system ranges from fast (microseconds) EMT, through electro-mechanical power swings (milliseconds), to slower modes influenced by the prime mover boiler and fuel feed systems (seconds to minutes). For the modeling of EMT caused by large disturbances, such as network faults and/or plant outages, system states must be evaluated at intervals in the order of milliseconds over time scales of seconds. For small-signal and voltage stability assessment, the time scale needs to be extended to minutes, and for voltage security tens of minutes to hours. During this period, accurate representation of power electronic devices requires relatively small time-steps, typical of EMT simulators, but impractical for phasor-type electromechanical dynamic simulation tools.

While EMT simulation software, such as EMTP-RV and PSCAD, represent the most accurate simulation tools available for detailed representation of power electronic devices, such tools are not practical for simulation of the dynamics of very large systems. The EMT simulation of a system with thousands of busses and many power electronic devices requires an excessive amount of time to simulate long transients at a very small time-step. Conversely, fundamental-frequency transient stability simulation software such as Eurostag, DigSilent and PSS/E enables very fast simulation, but such tools use relatively long integration steps in the order of 1 to 20 milliseconds. Consequently, highly non-linear elements, common in HVDC and FACTS devices, can only be represented as modified steady-state models. Since switching devices and control systems are not represented in detail, the overall accuracy of conventional transient stability programs suffers, and contingencies involving mal-operation of FACTS and AC-DC converter devices cannot be adequately represented.

As a result, these simulation tasks are currently performed using separate simulation tools, and significant compromises are required to deal with the respective shortcomings of the different simulations. The requirement to simultaneously simulate all mechanical, electrical and power electronic subsystems using heterogeneous tools provided by several software houses is becoming essential for many applications. Consequently, real-time digital simulators with the capability to integrate all necessary simulation tools in off-line or real-time co-simulation mode [43] have an advantage over real-time digital simulators based on closed computer systems that cannot execute third-party software.

C. Better Test Coverage in Complex Systems

The secure operation of power systems has become increasingly dependent on complex control systems and power electronic devices. Furthermore, the proliferation of DG plants, often based on the use of RES, presents significant challenges to the design and stable operation of today's power systems. Examples include the integration with the existing power grid of wind farms, photovoltaic cells, other power-electronic-based DG systems, domestic loads and future plug-in electric vehicles.

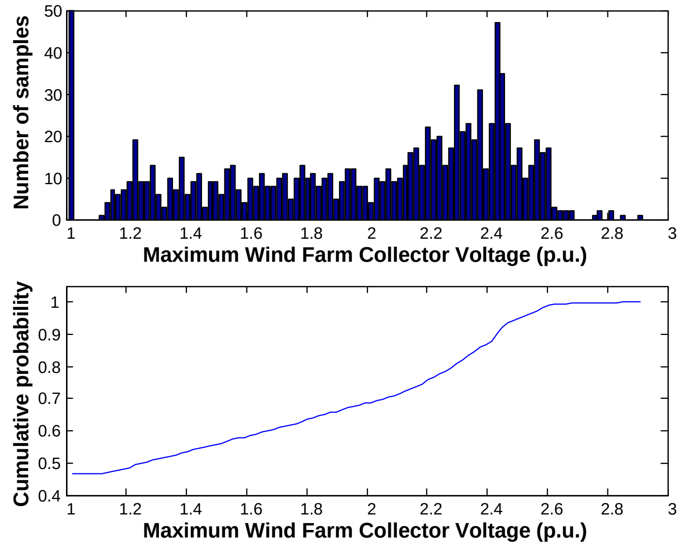


Figure 17: Example of Monte Carlo Statistical test: Windfarm Collector Over Voltage Characterization During a Fault

These applications take full advantage of multiple, very fast, and distributed power electronic systems that, in many cases, are of innovative design and may have never been integrated together, or with a power grid. In most cases, these distributed systems have been designed, manufactured and commercialized as individual off-the-shelf products, with no consideration given to total system performance. Validated models suitable for EMT, as well as dynamic stability analysis under normal and abnormal conditions, are usually not available. This poses a new and significant challenge to utility and system engineers who must guarantee total system performance and security.

With the help of real-time simulation, interactions with other control and protection systems, whether they are simulated or implemented in final hardware connected via HIL, can be easily analyzed and tested for a variety of normal and fault conditions. Therefore, when analytical methods fail to provide rigorous data on power system stability margins, currents and voltage intensity limits, statistical methods such as Monte Carlo studies, combined with real-time simulation, helps supply the missing data needed for the appropriate dimensioning of power system components [29]. Real-time simulation, in SIL or HIL configurations, can then significantly reduce the time required to complete the analysis. Since testing time is reduced, more tests can be performed, increasing coverage and statistical confidence in the results. Figure 17, for example, illustrates a statistical analysis of the overvoltage intensity at the collector of a wind farm for different fault durations and point-on-wave position of a particular wind turbine. Furthermore, conditions that would be costly and dangerous to create on a physical plant prototype or in a real power system can be reproduced using a real-time simulator capable of interfacing with fast-switching power electronic control & protection systems. Automated repetitive testing using a large number of samples can then help build statistical distributions, such as in a Monte-Carlo study. This provides valuable information that would be unattainable using offline tools. From this data, worst-case scenarios are identified and can be mitigated in advance.

VIII. Conclusion

Modern power systems continue to evolve requiring constant evaluation of new constraints. Major studies will require the use of very fast, flexible and scalable real-time simulators.

This paper has introduced a specific class of digital simulator known as a real-time simulator. By answering the questions “what is real-time simulation”, “why is it needed” and “where does it fit best”, the reader is better prepared to understand how real-time simulation can contribute to present and future research and study. Finally, by discussing the topics of results validation, the mixing of offline & real-time simulation and test coverage in complex systems, the role that real-time simulation can play in fast-evolving areas of power system development can be better understood.

IX. Acknowledgment

The authors gratefully acknowledge the contributions of Opal-RT Technologies customers and distributors who agreed to share their experience and applications of real-time simulation.

X. References

[1] *The American Heritage Dictionary of the English Language*. Boston: Houghton Mifflin Company, 2000.

[2] H. W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single-and Multiphase Networks," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, pp. 388-399, Apr. 1969.

[3] J. J. Sanchez-Gasca, R. D'Aquila, W. W. Price, and J. J. Paserba, "Variable time step, implicit integration for extended-term power system dynamic simulation," in *Proceedings of the Power Industry Computer Application Conference 1995*, Salt Lake City, UT, USA, 7-12 May 1995, pp.183-189

[4] D. Gillies. (2009, Oct.) Internet FAQ Archives. [Online]. http://www.faqs.org/faqs/realtime-computing/faq/

[5] J. R. Marti and J. Lin, "Suppression of numerical oscillations in the EMTP power systems," *IEEE Transactions on Power Systems*, vol. 4, pp. 739-747, May 1989.

[6] T. Noda, K. Takenaka, and T. Inoue, " Numerical Integration by the 2-Stage Diagonally Implicit Runge-Kutta Method for Electromagnetic Transient Simulations," *IEEE Transactions on Power Delivery*, vol. 24, pp. 390-399, Jan. 2009.

[7] Y. Shu, H. Li, and Q. Wu, "Expansion application of dSPACE for HILS," in *IEEE International Symposium on Industrial Electronics, 2008. ISIE 2008.*, 2008, pp. 2231-2235.

[8] C. A. Rabbath, M. Abdoune, and J. Belanger, "Effective real-time simulations of event-based systems," in *2000. Winter Simulation Conference Proceedings*, vol. 1, Orlando, 2000, pp. 232-238.

[9] M. O. Faruque, V. Dinavahi, M. Sloderbeck, and M. Steurer, "Geographically distributed thermo-electric co-simulation of all-electric ship," in *IEEE Electric Ship Technologies Symposium (ESTS 2009)*, 2009, pp. 36-43.

[10] R. Bednar and R. E. Crosbie, "Stability of Multi-Rate Simulation Algorithms," in *Proceedings of the 2007 summer computer simulation conference*, San Diego, 2007, pp. 189-194.

[11] R. Fang, W. Jiang, J. Khan, and R. Dougal, "System-level thermal modeling and co-simulation with hybrid power system for future all electric ship," in *IEEE Electric Ship Technologies Symposium (ESTS 2009)*, 2009, pp. 547-553.

[12] A. Kaddouri, B. Khodabakhchian, L. .-A. Dessaint, R. Champagne, and L. Snider, "A new generation of simulation tools for electric drives and powerelectronics," in *Proceedings of the IEEE International Conference on Power Electronics and Drive Systems (PEDS '99)*, 1999, vol. 1, pp. 348-354

[13] H. T. Su, K. W. Chan, and L. A. Snider, "Hybrid Simulation of Large Electrical Networks with Asymmetrical Fault Modeling," *International Journal of Modeling and Simulation*, vol. 28, no. 2, 2008.

[14] R. Kuffel, J. Giesbrecht, T. Maguire, R. P. Wierckx, and P. McLaren, "RTDS – a fully digital power system simulator operating in real time", *First International Conference on Digital Power System Simulators (ICDS '95)*, College Station, Texas, U.S.A., April 5-7, 1995, pp. 19-24.

[15] V. Q. Do, J.-C. Soumagne, G. Sybille, G. Turmel, P. Giroux, G. Cloutier, S. Poulin, “Hypersim, an Integrated Real-Time Simulator for Power Networks and Control Systems”, ICDS’99, Vasteras, Sweden, may 1999, pp 1-6.

[16] J. A. Hollman and J. R. Marti, "Real Time Network Simulation with PC-Cluster", *IEEE Trans. Power Systems*, 2008, vol. 18, no. 2, pp. 563-569.

[17] R. M. Ramanathan. Pogo Linux. [Online]. http://www.pogolinux.com/learn/files/quad-core-06.pdf

[18] J. Bélanger, V. Lapointe, C. Dufour, and L. Schoen, "eMEGAsim: An Open High-Performance Distributed Real-Time Power Grid Simulator. Architecture and Specification", Presented at the *International Conference on Power Systems (ICPS’07)*, Bangalore, India, December 12-14, 2007.

[19] M. Matar and R. Iravani, "FPGA Implementation of the Power Electronic Converter Model for Real-Time Simulation of Electromagnetic Transients", *IEEE Transactions on Power Delivery*, April 2010, vol. 25, issue 2, pp. 852-860.

[20] Wikipedia Fundation. (2009, Sep.) Wikipedia. [Online]. http://en.wikipedia.org/wiki/Model_based_design

[21] D. Auger, "Programmable hardware systems using model-based design", in *2008 IET and Electronics Weekly Conference on Programmable Hardware Systems*, London, 2008, pp. 1-12.

[22] G. Sybille and H. Le-Huy, "Digital simulation of power systems and power electronics using the MATLAB/Simulink Power System Blockset", in *IEEE Power Engineering Society Winter Meeting, 2000.*, Singapore, 2000, vol. 4, pp. 2973-2981.

[23] S.G.A. Perez, M.S. Sachdev, T.S. Sidhu, “Modeling relays for use in power system protection studies”, in the *2005 Canadian Conference on Electrical and Computer Engineering*, Saskatoon, Saskatchewan, Canada, 1-4 May 2005, pp. 566-569.

[24] H. Hanselmann, U. Kiffmeier, L. Koster, M. Meyer, and A. Rukgauer, "Production quality code generation from Simulink block diagrams", in *Proceedings of the 1999 IEEE International Symposium on Computer Aided Control System Design, 1999*, Kohala Coast, 1999, pp. 213-218.

[25] I. Sadasiva, F. Flinders, and W. Oghanna, "A graphical based automatic real time code generator for power electronic control applications," in *Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE '97)*, Guimaraes, 1997, vol. 3, pp. 942-947.

[26] C. Dufour, S. Abourida, J. Bélanger, "InfiniBand-Based Real-Time Simulation of HVDC, STATCOM and SVC Devices with Custom-Off-The-Shelf PCs and FPGAs," in *Proc. 2006 IEEE International Symposium on Industrial Electronics*, pp. 2025-2029.

[27] Y. Liu, et al., "Controller hardware-in-the-loop validation for a 10 MVA ETO-based STATCOM for wind farm application," in *IEEE Energy Conversion Congress and Exposition (ECCE'09)*, San-José, CA, USA, pp. 1398-1403.

[28] I. Etxeberria-Otadui, V. Manzo, S. Bacha, and F. Baltes, "Generalized average modelling of FACTS for real time simulation in ARENE," in *IEEE 28th Annual Conference of the Industrial Electronics Society (IECON 02)*, 2002, vol. 2, pp. 864-869.

[29] J.N. Paquin, J. Bélanger, L.A. Snider, C. Pirolli, and W. Li, "Monte-Carlo Study on a Large-Scale Power System Model in Real-Time using eMEGAsim," in *IEEE Energy Conversion Congress and Exposition (ECCE'09)*, San-José, CA, USA, pp. 3194 - 3202

[30] J.N. Paquin, J. Moyen, G. Dumur, V. Lapointe, "Real-Time and Off-Line Simulation of a Detailed Wind Farm Model Connected to a Multi-Bus Network", *IEEE Canada Electrical Power Conference 2007*, Montreal, Oct. 25-26, 2007.

[31] J. .-N. Paquin, C. Dufour, and J. Bélanger, "A Hardware-In-the-Loop Simulation Platform for Prototyping and Testing of Wind Generator Controllers" in 2008 CIGRE Conference on Power Systems, Winnipeg, Canada. October 19-21, 2008.

[32] C. Dufour, T. K. Das, S. Akella,"Real Time Simulation of Proton Exchange Membrane Fuel Cell Hybrid Vehicle", Proceedings of the 2005 Global Powertrain Congress (GPC-05), Sept. 27-29, 2005, Ann Arbor, MI, USA.

[33] C. Dufour, T. Ishikawa, S. Abourida, and J. Belanger, "Modern Hardware-In-the-Loop Simulation Technology for Fuel Cell Hybrid Electric Vehicles", in *IEEE Vehicle Power and Propulsion Conference (VPPC 2007)*, Arlington, TX, USA, 9-12 Sept. 2007, pp. 432-439.

[34] C. Dufour, J. Bélanger, T. Ishikawa, K. Uemura, "Advances in Real-Time Simulation of Fuel Cell Hybrid Electric Vehicles", ", Proceedings of the 21st Electric Vehicle Symposium (EVS-21), April 2-6 2005, Monte Carlo, Monaco

[35] C. Dufour, G. Dumur, J. .-N. Paquin, and J. Belanger, "A multi-core pc-based simulator for the hardware-in-the-loop testing of modern train and ship traction systems," in the *13th Power Electronics and Motion Control Conference (EPE-PEMC 2008)*, Poznan, Poland, 1-3 Sept. 2008, pp. 1475–1480.

[36] J.N. Paquin, W. Li, J. Belanger, L. Schoen, I. Peres, C. Olariu, H. Kohmann, "A Modern and Open Real-Time Digital Simulator of All-Electric Ships with a Multi-Platform Co-Simulation Approach", *Proceedings of the 2009 Electric Ship Technologies Symposium (ESTS 2009)*, Baltimore, MD, USA, April 20-22, pp. 28-35

[37] Radio Technical Commission for Aeronautics, "Software Considerations in Airborne Systems and Equipment Certification," Radio Technical Commission for Aeronautics Standard DO-178B, 1992.

[38] Radio Technical Commission for Aeronautics, "Design Assurance Guidance for Airborne Electronic Hardware," Radio Technical Commission for Aeronautics Standard DO-254, 2000.

[39] J. Bélanger, H. Blanchette, and C. Dufour, "Very-high Speed Control of an FPGA-based Finite-Element-Analysis Permanent Magnet Synchronous Virtual Motor Drive System," in *IEEE 34th Annual Conference of Industrial Electronics (IECON 2008)*, Orlando, FL, 10-13 nov. 2008, pp. 2411-2416.

[40] W. Min, S. Jin-Hua, Z. Gui-Xiu, and Y. Ohyama, "Internet-Based Teaching and Experiment System for Control Engineering Course," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, 2008.

[41] J.-J. Huselstein, P. Enrici, and T. Martire, "Interactive Simulations of Power Electronics Converters," in *12th International Power Electronics and Motion Control Conference (EPE-PEMC 2006)*, Portoroz, 2006, pp. 1721-1726

[42] M. Harakawa, H. Yamasaki, T. Nagano, S. Abourida, C. Dufour, J. Belanger, "Real-Time Simulation of a Complete PMSM Drive at 10 µs Time Step", Presented at the *International Power Electronics Conference, 2005 (IPEC 2005)*, Niigata, Japan, 2005

[43] J.-F. Cécile, L. Schoen, V. Lapointe, A. Abreu, and J. Bélanger. (2006) www.opal-rt.com. [Online]. http://www.opal-rt.com/technical-document/distributed-real-time-framework-dynamic-management-heterogeneous-co-simulations

[44] K. Strunz and E. Carlson, "Nested Fast and Simultaneous Solution for Time-Domain Simulation of Integrative Power-Electric and Electronic Systems," *IEEE Transactions on Power Delivery*, Jan. 2007, vol. 22, no. 1, pp. 277-287.

XI. Biographies

Jean Bélanger (M'88) is the President, CEO and founder of Opal-RT Technologies, Inc. He is an expert in Real-Time Simulation of power systems, with more than 25 years of experience in the field, including many years as part of the Simulation division of Hydro-Quebec where he helped developed the world's first 735 kV power transmission systems. He received his M.Sc. from Laval University, Quebec. Since 2001, Mr. Bélanger is a fellow of the Canadian Academy of Engineering.

Philippe Venne (S'99) received the B.Eng. in computer engineering from Université du Québec à Hull, Canada in 2002 and the M.Sc. degree from Université du Québec à Rimouski, Canada in 2006. While enrolled as a Ph.D. student with the Aalborg University in Denmark, he joined Opal-RT Technologies in 2009 as a Power Systems Simulation Specialist with the EMS team. His professional interests include wind turbine simulation and control, as well as smart grids.

Jean-Nicolas Paquin (M'08) is a Power Systems Simulation Specialist at Opal-RT Technologies since 2007, and leader of the Modeling and Simulation R&D team (EMS). He received his M.Eng. degree in 2006 from École de Technologie Supérieure (ÉTS) in Montreal, Canada. His professional interests include the simulation and study of HVDC control and protection systems as well as inverter-based DG. He is involved in real-time simulation expertise and consulting services.