A Modern and Open Real-Time Digital Simulator of Contemporary Power Systems

Jean Bélanger, Laurence A. Snider, Jean-Nicolas Paquin, Claudio Pirolli, Wei Li

***Abstract*— This paper describes a versatile, multi-domain, real-time digital simulator of large power grids. Its capability to conduct multiple tests for protection coordination studies is described. A large grid model built using the EMTP-RV software and simulated in real-time using the eMEGAsim real-time digital simulator and EMTP-RT software tool is described. Comparisons between off-line and real-time simulations with different solvers are made using superimposed steady-state and fault condition waveforms. A multiple random tests application for protection coordination studies using eMEGAsim simulator's built-in software TestDrive GUI and Python API scripting tool is described. The paper concludes with a discussion on the off-line, real-time and acceleration modes of simulation of the PC-based eMEGAsim simulator and its advantages for studies of modern power systems.**

***Index Terms*-- real-time simulation, accelerated simulation, off-line simulation, electrical network, wind energy, detailed modeling, doubly-fed induction generator, electromagnetic transients, hardware-in-the-loop, multi-core processors**

I. INTRODUCTION

SIMULATORS have been extensively used in the planning and design of transmission systems for decades. Simulator technology has evolved from physical/analogue simulators (HVDC simulators, TNA's) for electromagnetic transients and protection and control studies, to hybrid TNA/Analogue/Digital simulators with the capability of studying electro-mechanical transient behaviour [1], to fully digital real-time simulators.

Physical simulators served their purpose well, however they were very large, expensive and required highly skilled technical teams for the tedious job of setting up networks and maintaining the extensive inventory of complex equipment. With the development of microprocessors and floating-point DSPs, physical simulators have been replaced with fully digital real-time simulators.

DSP-based real-time simulators for use in (HIL) hardware-in-the-loop studies became available first [2]. However, the limitations of using proprietary hardware were soon recognized and commercial supercomputer-based simulators such as HYPERSIM from Hydro-Quebec [3] were developed. Hydro-Quebec has since ceased commercializing their Hypersim product. Attempts have been made by a number of universities and research organisations 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 [4]. Such development was very difficult due to the lack of fast, low-cost inter-computer communication links. However, the advent of low-cost, easily obtainable multi-core processors [5] (INTEL or AMD) and related Commercial-off-the-Shelf (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 with 8 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 fast inter-computer communication technology.

COTS-based high-end real-time simulators using INTEL or AMD multi-core processor computers have been used in aerospace, robotics, automotive and power electronic system design and testing for a number of years [6]. Recent advancements in multi-core processor technology means that such simulators are now available for the simulation of electromagnetic transients expected in large-scale power grids, micro-grids, wind farms and power systems installed in large electrical ships and aircraft. These simulators, operating under Windows, LINUX and standard real-time operating systems, are potentially compatible with all power system analysis software 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.

This paper discusses the simulation challenges involved and solutions implemented in the digital real-time simulation of large-scale power systems with integrated power-electronic

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devices and control systems. Off-line and real-time simulation results obtained through the use of the PC-based eMEGAsim simulator [6], equipped with the latest INTEL quad-core processors, will be presented and compared with results obtained with the famous EMTP-RV off-line simulation tool[1].

II. NEW CHALLENGES FOR POWER SYSTEM ENGINEERS AND SIMULATOR MANUFACTURERS

A. Application Challenges

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

The above applications take full advantage of several very fast and distributed power electronic systems which, in many cases, are of innovative design and consequently have never been integrated together or with a power grid. Furthermore, in most cases, these distributed systems are designed, manufactured and commercialized as individual off-the-shelf products, with no consideration given to total system performance. Validated models suitable for electromagnetic transients, 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.

B. Simulation Challenge 1: Simultaneous Simulation of Fast and Long Phenomena

Simultaneous simulation of fast and long phenomena pushes simulation tools that are required in the planning and operation of power systems to their limits. Indeed, such challenges are multi-disciplinary. Examples include mechanical stresses on large generators due to potential sub-synchronous resonance and sudden loss of loads; rotation of wind turbine palms in front of the mast, creating pulses on mechanical and electrical torques of generators which must be compensated for by special control loops; electrical systems installed on large electrical ships involve the simulation of several interconnected generators and propulsion plant, together with the complex behaviour of the water and the propeller.

The transient response of an interconnected power system ranges from fast (microseconds) electromagnetic transients, 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 electromechanical transients (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 require relatively small time steps, typical of electromagnetic transients (EMT) simulators, but impractical for phasor-type electromechanical dynamic simulation tools.

C. Simulation Challenge 2: Small Time Step

It is a common practice with EMT simulators to use a simulation time step of 30 to 50 µs to provide acceptable results for transients up to 2 kHz. Better precision can be achieved with smaller time steps. Simulation of transient phenomena with frequency content up to 10 kHz typically requires a simulation time step of approximately 10 µs. Power electronic converters with higher PWM carrier frequency in the range of 10 kHz, such as those used in low-power converters, require smaller time steps of less than 250 nanoseconds without interpolation, or 10 µs with an interpolation technique. AC circuits with higher resonance frequency and very short lines, as expected in a low-voltage distribution circuit and railway power feeding system may require time steps below 20 µs. Tests must be done with practical system configurations and parameters to determine minimum time step and the number of processors required to reach the minimum time step.

Modern PC-based simulators such as eMEGAsim can exhibit jitter and overhead of less than 1µs which enable time step values as low as 10 µs with plenty of processing resource per processor core available for computation of the model. Simulation time steps can therefore be reduced to a very low value when necessary to increase precision or to prevent numerical instability.

D. Simulation Challenge 3: Multi-domain Simulation with Heterogeneous 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 would require an excessive amount of time to simulate long transients at very small time step when using only one processor. Conversely, fundamental-frequency transient stability (TS) simulation software enables very fast simulation, but such tools use relatively long integration steps in the order of 10 to 20 milliseconds; consequently, highly non-linear elements common in HVDC and FACTS 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 converters devices cannot be adequately represented.

Consequently, all 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 parallel processor simulators with the capability to integrate all necessary simulation tools in off-line or real-time co-simulation mode [7] are certainly an advantage over real-time digital simulators using closed computer systems that cannot execute third-party software.

III. REAL-TIME SIMULATION AND HIL APPLICATIONS

A. Rapid Control Prototyping with Physical Plant

The use of real-time simulators during two different design phases is illustrated in Fig. 1. A classic use of such simulators is the design of controllers using a prototype controller connected to a physical model of the plant. This is called Rapid Control Prototyping.

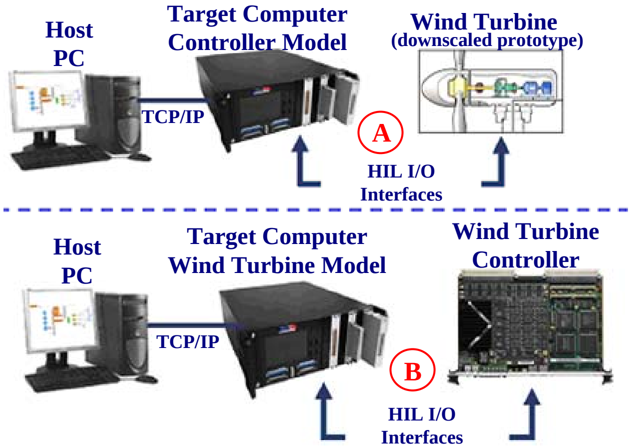


Fig. 1. Real-Time simulation in various design phases: A) Model-Based Design B) Rapid Control Prototyping

In this case (Fig 1-A), the prototype controller or protection system is connected in closed-loop with a physical prototype of the real plant. The control or protection systems are implemented with electronic components or in C-code or other language used for modern digital controllers. Some manufacturers of power system controller and protection equipment now use de-facto industry standard tools like SIMULINK [8] and Real-Time Workshop (RTW) or eCODER [9] automatic code generators; common practice for years in the aerospace and automotive industries. Using visual simulation tools and code generators facilitate system modeling, specification and documentation. This technique, called fast control prototyping, is now being adopted by most organisations, whenever possible.

B. Full Hardware-In-The-Loop (HIL) Simulation

In the case of more complex plants such as aircraft and power systems, the Model-Based Design technique is a better choice from both an economic and practical point of view. In this case (Fig 1-B), the prototype or real controller is connected in HIL mode to a powerful real-time simulator capable of simulating complex plants such as aircraft, vehicles, and large power grids in real-time with sufficient fidelity to test the performance of the controller and other intelligent devices under development or during the final system integration test.

Interaction with other control and protection systems, whether simulated or implemented in the final hardware connected in HIL mode, can then be easily analysed for a variety of normal and fault conditions. Conditions that are costly and dangerous to create on a physical plant prototype or on the real system during commissioning can be easily reproduced using a real-time digital simulator capable of interfacing with fast power electronic controls and protection systems.

The use of detailed models or actual controller hardware is required in HIL simulation and testing to get results as near as possible to real world. Of course, the use of advanced off-line modeling software is also required at the planning stage when protection equipment and controllers are not yet available. The capability to use the same parallel computer for off-line simulation and real-time HIL tests provides additional value to the user.

IV. SIMULATION ENVIRONMENT

A. SPS/Simulink

Simulink is the dominant, graphical interfaced, modeling and simulation tool, used in many engineering fields. SimPowerSystems (SPS) [10] developed by Hydro-Quebec Research Center (IREQ) is a Simulink toolbox that provides multiple model components, all based on electromechanical and electromagnetic equations, for the simulation of power systems and machine drives [11]. Both tools are available as part of the MATLAB software suite for mathematical processing. By using the toolboxes included in MATLAB, it is possible to easily model any power system device and control. Users can also easily develop their own models.

SPS uses the state-variable analysis approach to solve power system equations. The linear differential equations can either be represented with continuous or discrete state-spaces. Although the use of fixed-step algorithms is required for real-time simulation, it is also possible to solve system equations using variable-step integration techniques within the Simulink environment. However, the SPS toolbox is designed for off-line simulation of electrical systems and is not optimized for hard-real-time and parallel simulation.

B. SPS/Simulink on eMEGAsim

Simulink has emerged as a worldwide standard for scientific computing. It is widely used in the aerospace and automotive industries in combination with the popular Real-Time Workshop C-Code generator [9] to conduct real-time simulation of electro-mechatronic systems. This adaptation to real-time simulation of power systems is achieved through the use of solvers optimized for real-time simulation of electrical networks such as ARTEMiS [12] and real-time distributed software platforms such as RT-LAB, both of which have been used in a number of industrial sectors for more than 10 years. In addition to SPS/Simulink, ARTEMiS and RT-LAB, eMEGAsim uses RT-Events, which is optimized for real-time simulation of voltage-source power electronic converters (VSC), used in modern FACTS and AC-DC converters [13], power grids, micro grids and power systems embarked in automobile, aircraft, trains and ships. These same tools have been used for several years by major hybrid vehicle and power electronic system manufacturers [14].

C. ARTEMiS Real-Time Solver

The solver used with eMEGAsim enables real-time simulation by pre-calculating system equations of state-space model parameters that are stored in memory and loaded in real-time for each circuit topology depending on switch status. ARTEMiS also includes a set of special mathematical solving techniques based on the well known L-stable approximations of the matrix exponential. L-stability is an extension of A-stability in which most numerical oscillations are naturally suppressed [11][12]. In this paper, the art5 solver (5th order numerical technique), one of the discrete integration techniques available with ARTEMiS is mostly used. This solver is available for both off-line and real-time simulation modes.

This tool comes with a library of essential decoupling elements for the distributed simulation of the system state-space equations to take advantage of modern multi-core processors and PC clusters. The decoupling is either naturally made with Bergeron traveling-wave power line models with inherent delays or artificially added by substituting transformer inductances or shunt and series capacitors with a distributed model enabling the solution of the state-space systems in parallel. The same technique is applied by all research centers and private organizations using parallel computers to simulate large power systems. Of course, such techniques add high-frequency poles and zeros close to the simulation sampling frequency, which is typically 20 kHz to 100 kHz. This high-frequency error is generally accepted for the evaluation of slow dynamic transients, temporary overvoltage, harmonics and switching transients up to 2 to 5 kHz as well as for the performance evaluation of protection and power electronic controllers.

D. EMTP-RV for Off-Line Simulation

EMTP-RV is a revised version of the well-known EMTP software which is considered to be a standard tool by many power system specialists. EMTP-RV provides a user-friendly graphical interface, named EMTPWorks, to construct and edit large one-line circuit diagrams that allow detailed modeling of network components including control, linear and non-linear elements [15][16].

The computation engine of EMTP-RV represents the power system's differential equations using a modified-augmented version of the well-known nodal analysis approach [17]. It uses the trapezoidal numerical integration technique as well as the backward Euler method to solve the system's equations. A major drawback of the trapezoidal method is that oscillations are undamped when switching events or discontinuities occur. It is also known that backward Euler cannot be used by itself to solve complex system equations because it is not sufficiently accurate, being a first order numerical integration method. In order to overcome these weaknesses, EMTP-RV has an optional combination of both numerical integration techniques to get stable and accurate simulation in the fastest time. It uses the trapezoidal method with a fixed-step **Ts** and an additional backward Euler iteration once every half step **Ts/2** whenever a discontinuity occurs. This combined corrector method provides good accuracy for the solution of system equations. However, this calculation approach has not yet been implemented for parallel and real-time simulation.

As in SPS/Simulink, controls as well as power devices can be modeled. Fundamental frequency load-flow as well as impedance frequency scan solution are implemented in addition to the time-domain electromagnetic transient simulation. This set of tools, developed by universities and research centers associated to major utilities, such as EDF and Hydro-Quebec, is certainly an asset to the power system industry.

E. eMEGAsim and EMTP-RT

The demands by EMTP-RV users for faster and real-time simulation exploiting modern multi-core processors and clusters have created an interest for its use in combination with eMEGAsim. EMTP-RT (for Real-Time interface to EMTP-RV) seamlessly integrates key eMEGAsim features into the modeling environment of EMTP-RV. It includes real-time simulation capabilities, together with the ability to separate models for execution on multiple processor cores, with the integration of both SPS/Simulink and existing eMEGAsim toolboxes optimized for power electronic system simulation as illustrated on Fig. 2.

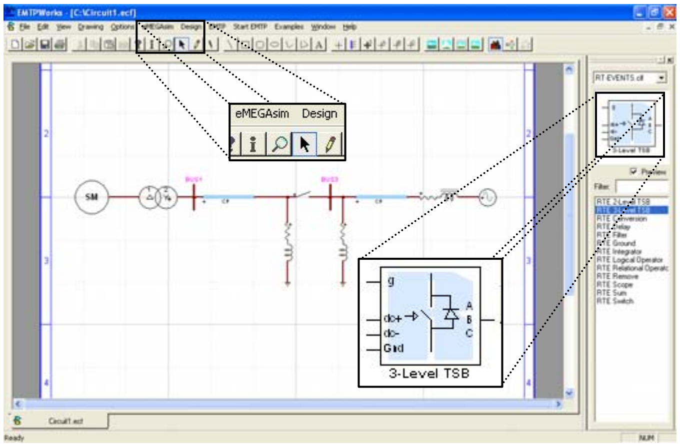


Fig. 2. EMTPWorks and the integration of EMTP-RT combined with special component libraries.

The principle of this feature consists of the automatic conversion of an EMTP-RV model to an SPS/Simulink model which includes data transfer, data conversion and model compilation. This process occurs by clicking on the eMEGAsim menu item at the top of the EMTPWorks window, as illustrated in Fig. 2, and is achieved automatically within seconds without the need for user intervention. The SPS model can then be opened for modification using SPS/Simulink blocks and/or for off-line simulation in the MATLAB environment as well as for real-time simulation with eMEGAsim. Complete automation and processor allocation is planned within the next few months.

EMTP-RT takes advantage of all tools provided in EMTP-RV, such as off-line Load-Flow solution and Frequency Scan type of analysis, combined with the power of real-time and accelerated simulation provided by eMEGAsim and the flexibility of Simulink for control design and other toolboxes for multi-domain simulation. Current EMTP-RV users now have the ability to conduct HIL testing with their EMTP-RV models without the need to migrate to unfamiliar software or manually convert their model and data, which is very time consuming and prone to errors.

The Load-Flow and steady-state solutions obtained with EMTP-RV can be used to initialize machines and control states in real-time simulations. Of course, very high-frequency models used to simulate lightning strike transients are not converted for use in the eMEGAsim and SPS environment.

F. *Numerical Techniques and Fixed Step-Size Selection*

In order to perform an easy assessment of different solvers and step-sizes, a simple RLC circuit was modeled using both the eMEGAsim/SPS/ARTEMiS and EMTP-RV off-line simulation environments, with different solvers. The schematic diagram of this model is depicted in Fig. 3.

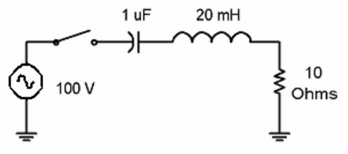


Fig. 3. Simple RLC model for the assessment of numerical solvers.

The circuit is composed of a 100 V peak single-phase voltage source connected to an RLC element with a resonance frequency of 1125 Hz (10Ω, 20mH, 1μF), through an ideal switch. The simulation starts with the ideal switch opened and with no current flowing through the RLC passive elements. The capacitor voltage is initialized at 100 V. At t=0.01s, the ideal switch is closed and a transient response is observed through the measurement of the capacitor voltage. The capacitor voltage during this test is illustrated in Fig. 4.

The circuit energization provokes oscillations at the resonance frequency of the RLC circuit (1125 Hz), which, when simulated at 100μs, (a rate near the practical Nyquist rate of 10 times the bandwidth), is considered hard to represent accurately with low-order integration techniques.

The circuit was first simulated at 10μs with both the eMEGAsim Trapezoidal solver (SPS/Simulink) and Trapezoidal-backward-Euler technique of the EMTP-RV software. These two tests provide the reader with a reference value which represents the ideal precision of the simulation as they are made at a sampling frequency of 100 times the bandwidth of the circuit. As can be observed in Fig. 5, these two dashed waveforms follow each other very accurately.

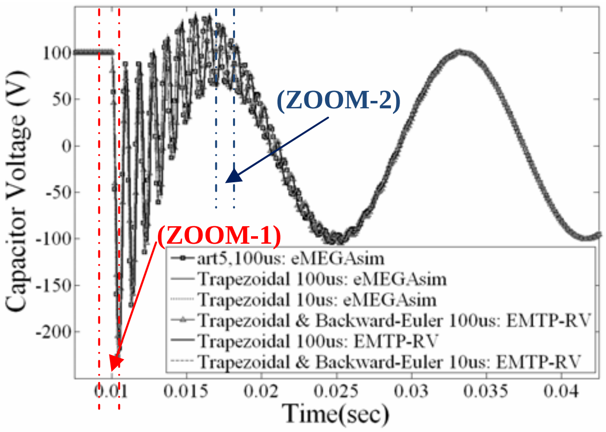


Fig. 4. Capacitor voltage during RLC energization using an ideal switch

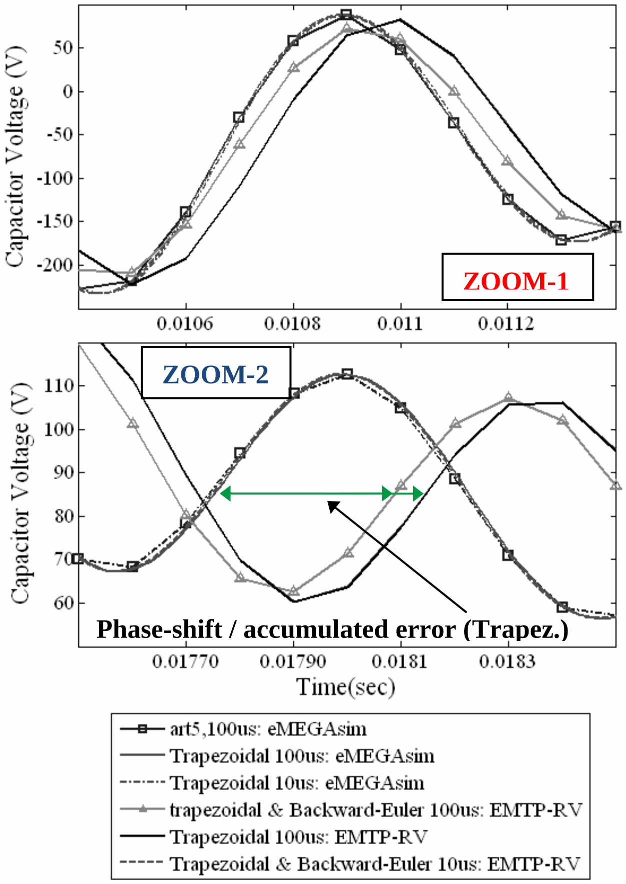


Fig. 5. Capacitor voltage during RLC energization – ZOOM-1 and ZOOM-2

A last test was done using the eMEGAsim ARTEMiS “art5” integration technique and the waveform is represented in Fig. 5 as squares attached with straight black lines.

An insight illustrated in Fig. 5 shows that the Trapezoidal technique accumulates a numerical error as the simulation time increases (ZOOM-1 vs ZOOM-2). This phenomenon results in a phase-shift with respect to the waveforms obtained at 10 µs.

The combined Trapezoidal-Backward-Euler algorithm of EMTP-RV is unleashed for a few steps (tolerance dependant), only when a discontinuity such as a switch state toggles. This technique will avoid numerical instabilities and offer better precision for the period in which it is activated. By comparing the Trapezoidal technique and the Trapezoidal-Backward-Euler at 100µs, one observes a phase-shift between their correspondent waveforms in Fig. 5. This phase-shift is induced at the first few steps after the ideal switch is toggled, as the Trapezoidal solver at 100µs starts accumulating numerical errors earlier than the Trapezoidal-Backward-Euler at 100µs.

As illustrated in Fig. 5, the L-stable property of art5 (eMEGAsim) seems to offer the best accuracy for this particular application. Indeed, the corresponding waveform follows the reference accurately despite the relatively low sampling rate (100µs).

Regardless of simulation environment, both the performance of the numerical solver and the bandwidth of interest must be considered when it comes to selecting the sampling rate. The standard approach for selecting a suitable fixed step-size for models with increasing complexity is the time-domain comparison of waveforms for repeated runs with different step-sizes.

V. SIMULATION OF A LARGE NETWORK USING EMTP-RT

Real-time simulation of large power systems integrated with a wind farm has already been presented in [18]. More than 10 wind turbines with detailed AC-DC-AC power electronic converters modeled in detail were simulated in less than 50 µs with seven (7) processors. The large power system model depicted in Fig. 6 presents a network with a very large number of busses and sort lines. It was first built and tested within the EMTP-RV environment. Using the EMTP-RT software tool, it was then converted to the SPS/Simulink environment as a distributed model, ready to use with the eMEGAsim real-time simulator.

This section describes the model and validates the accuracy and similarity of EMTP-RV and real-time eMEGAsim (SPS/Simulink) environments by comparing results in steady-state and in fault condition.

A. Network Model Description

The 60 Hz, 138/230kV HVAC power system model is an 86-bus electrical network. Its 86 transmission lines supply power to a total of 23 loads, rated at 413 MVA (403 MW, 91MVAR) each. Nine ideal voltage sources with lumped equivalent impedance are representing the generators. Full machine dynamics can easily be added.

Distributed parameters line models are used for the representation of long lines. As in (1) this type of line's transport delay τ (in seconds) is defined by:

$$\tau = d\sqrt{LC} \tag{1}$$

where d is the line length in km, L is the line inductance in H/km and C is the line capacitance in F/km. Since its transport delay is proportional to its line length, the distributed parameter line can only be accurately simulated with very small sampling times for very small lengths. PI section models have to be used for the representation of smaller lines for real-time simulation using practical fixed-time step within 10 to 50 µs to achieve hard real-time performance. In the studied network, some lines were sectionalized into multiple short parts for the study of faults at various locations. Sixty (60) three-phase PI section lines with self and mutual impedance representation and 26 distributed parameter lines were used. All line sections with a length of 20 km and shorter were simulated using PI sections to achieve a time step of 50 µs. The shortest line length is 0.85 km.

The model was parallelized on 7 processor cores of an 8-core eMEGAsim target computer. To avoid unrealistic high-frequency oscillations, the electrical circuit was distributed using ARTEMiS lines and stublines in strategic parts of the model, thus adding only "natural" delays between sections.

This technology constraint is common to all commercially available real-time simulators. Most of the system separation was done using optimized distributed parameters lines from the eMEGAsim's ARTEMiS toolbox. As they are long lines, their intrinsic delay permits reliable distribution without affecting the dynamic property of the system.

Exceptions were made by using the transformer T1 (separation of CPU 1 and CPU 7) and transformers T2 and T3 (separation of CPU 4 and CPU 5) as decoupling elements. A special three-phase decoupling transformer model was used. It has secondary winding impedances modeled with distributed inductances. The distributed inductance and capacitance model, often referred to as a stubline model, is widely used in real-time simulation because of its special property: it is similar to a distributed parameter transmission line but with a transport delay τ of exactly one time step. With wisely chosen parameters, the stubline will provide a very good approximation of the system behavior when used as an inductor or capacitor replacement and system separation device to facilitate parallel processing. Of course, distributed inductors and capacitors add parasitic capacitors and inductors respectively.

B. Steady State Comparison

For this test, voltage measurements were made on preselected buses. The steady-state voltages were measured in both simulation environments for assessment. A comparative bar graph is shown in Fig. 7.

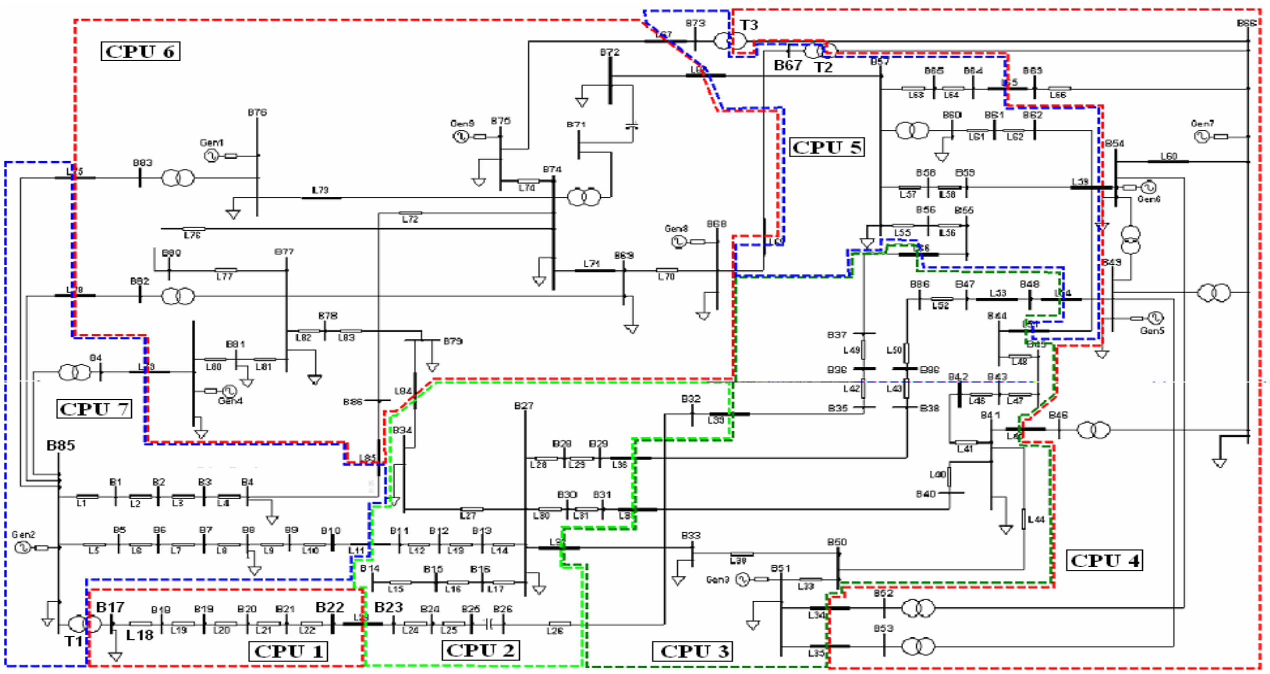


Fig. 6. Schematic diagram of the network model

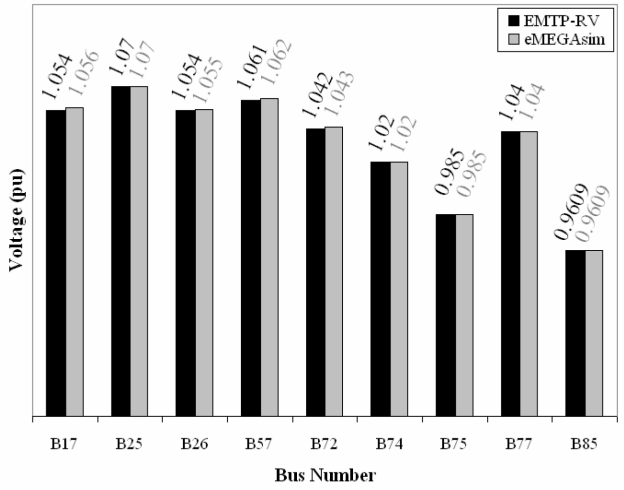


Fig. 7. Comparison of steady-state voltage at selected locations

As seen in Fig. 7, most of the displayed steady-state results perfectly match. Slight differences are seen at some buses as the largest difference is of 0.002 pu. The steady-state test reveals an accurate match and similarity for the computation of steady-state conditions in both simulation environments.

C. Three-Phase Fault at Bus B22

The waveform of the phase-a current measured through line L18 is shown in Fig. 8 for a three-phase fault applied at Bus B22. Both waveforms match very accurately in steady-state and during the 50 ms three-phase fault. Slight differences are observed at fault extinction. The results are displayed for both simulation environments, at 50µs and 1µs. The combined Trapezoidal-Backward-Euler Technique was used in EMTP-RV and the art5 solver was used in eMEGAsim.

At t = 1.105 s, the fault is applied and a transient peak current of about 7 pu is observed on the current waveform. For a given step-size, slight differences are observed from fault extinction. As one can observe in Fig. 8 (ZOOM), amplitude deviations between EMTP-RV and eMEGAsim waveforms are observed. At 50 µs, a maximum deviation of 0.03 pu between waveforms obtained in both environments is observed whereas at 1µs, this value is measured as no more than 0.01 pu. However, the waveforms obtained with both environments (Trapezoidal-Backward-Euler VS art5) are mostly in agreement as they follow the same trajectories at a given step-size.

A first concluding statement on these simulation results is that for this test on this particular circuit, the element models in both EMTP-RV and SPS/Simulink are shown as acceptable equivalents, despite the differential equations representation approach (e.g. Nodal VS State-Space). It can also be observed that the different numerical techniques used do not cause any critical differences in simulating accurately this large network model. The EMTP-RT software is thus presenting two major advantages: 1) it is a great tool to help in model cross-validation in two different simulation environments; 2) it is very useful for present EMTP-RV users who wish to simulate their power system models in real-time without any fastidious manual model conversions.

Moreover, reducing the step-size (usually gradually) is a relevant technique for measuring/evaluating the model bandwidth and the desired level of precision. As for the presented power system, simulating a distribution network, with very short lines, thus relatively fast oscillation modes activated by transient operations, may require user experience and knowledge. For instance, an engineer who would like to perform a protection study, a transient stability or voltage stability study on such a network model may determine as "good enough" the use of a 50 µs step-size. However, a 1 µs step-size may be more suitable for an exhaustive harmonic study during transient operation.

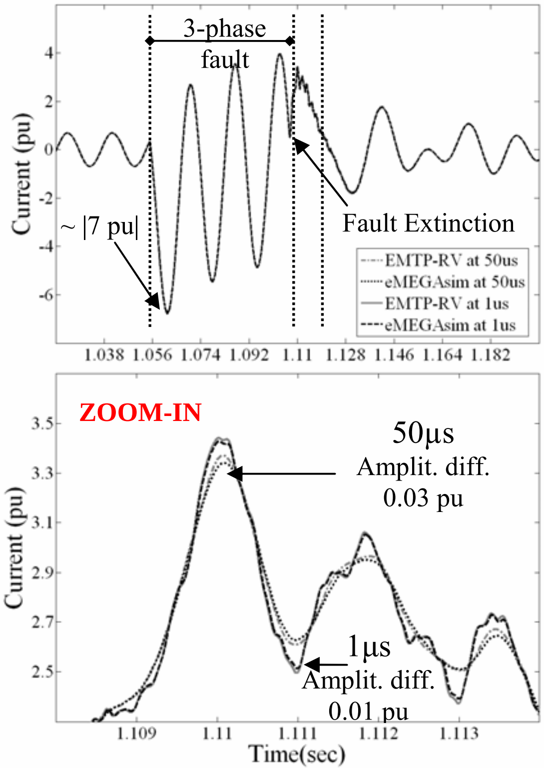


Fig. 8. Phase-a current through line L18 during three-phase fault at bus B22

It is important to remember however that with any COTS technologies [6] or custom processor-based real-time simulators [2], a 1 µs time-step for such a complex network is not achievable. When performing studies requiring Real-Time testing such as dynamic protection testing, HVDC or FACTS controller testing, or smart-grid high-level controller testing, making a "good-enough accuracy VS computation performance" compromise is sometimes inevitable. With the current COTS processor-based technology of eMEGAsim, real-time performance could be achieved with a step-size in the range of 10-20 µs, depending on model complexity and hardware availability. This would require additional processors, which implies clustering multiple 8-core real-time target computers together with very fast and low latency commercial communication links available with eMEGAsim.. Particular applications requiring very low step-sizes are currently achievable using FPGA technology along with the RT-XSG blockset, which is also available with the eMEGAsim platform [6].

VI. MULTIPLE RANDOM TESTS AND STATISTICAL STUDIES FOR PROTECTION AND INSULATION COORDINATION

Protection and insulation coordination techniques make use of statistical (Monte-Carlo) studies, in order 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 is applied. For protection coordination studies, multiple fault scenarios are required to determine appropriate protective relay settings and correct equipment sizing. By testing multiple fault occurrences, the measured quantities are identified, recorded and stored in a database for later retrieval, analysis and study. While traditional off-line software tools (e.g. EMTP) may be used for Monte Carlo studies in the development of protection algorithms, once an actual hardware relay is built its evaluation and further development may require a real time simulator. Typical studies include digital relay behavior evaluation in different operating conditions of the power system. Furthermore, relay action may influence the power system, may increase distortions, and thus affect other relays. It's a two-way street and closed loop study in real time is a must for many system studies and protection system development.

This section presents a simple model with multiple random tests programmed and applied using features of the eMEGAsim real-time simulator.

A. Application Description

The system under study illustrated in Fig. 9 is a 230 kV, 60Hz HVAC simplified power system model, which consists of a radial feeder of two parallel transmission lines transiting power from BUS 1 to BUS 2.

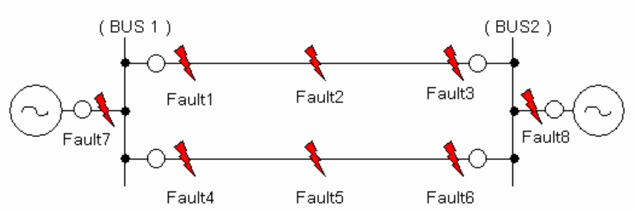


Fig. 9. Simplified network used for multiple random test study

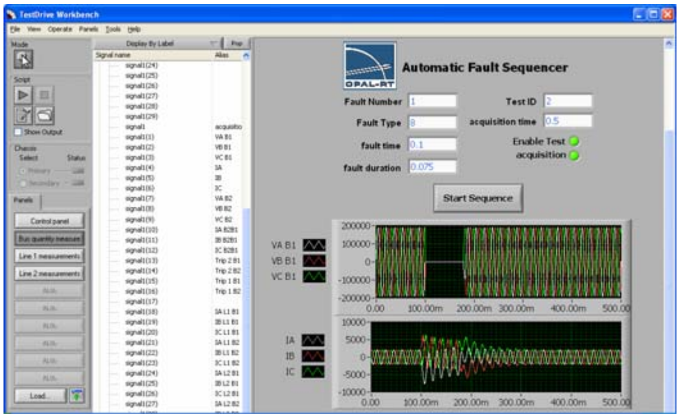
Ideal voltage sources with lumped equivalent impedances are used to represent the generators. A total of 4 distributed parameter lines of 10 km are used to represent the two 20 km long radial lines. Faults can be applied in the middle of both lines. All studied fault positions are illustrated on Fig. 9.

The automation of the test sequences was done using a Python API script which is executed within a graphical user interface (GUI), TestDrive, featured within the eMEGAsim simulation platform. Results are also observed on the TestDrive GUI.

B. TestDrive GUI as a Test Sequence Display and Control

Simulink interfaces (scopes, dials, etc.) can quickly become inadequate with complex power grid statistical studies. In this particular case, it is desirable to display data triggered on faults during and after the test sequences. TestDrive, the featured GUI of the eMEGAsim platform has an interface based on the LabVIEW software from National Instruments and can also be scripted using Python APIs. Using the LabVIEW runtime engine, it enables users to build display and control panels and virtually connect real-time model signals and parameters to graphical displays. TestDrive also has built-in display triggering capability that enables the display of complex waveforms in real-time and their synchronization with specific events.

The GUI built for the application is shown on Fig. 10, where the voltage and current results of a three-phase to ground fault applied at BUS 1 is displayed. The fault in question is a three-phase-to-ground fault applied at BUS1. The scopes of the GUI will display the voltages and currents as measured at BUS 1. The test sequencing is synchronized on steady-state voltage zero-crossings, which permits precise triggering and fault timing. In this example the fault was scheduled to start 100 ms after scope trigger instant with duration of 75 ms.



Fault Number 1
Test ID 2
Fault Type 8
acquisition time 0.5
fault time 0.1
fault duration 0.075
Enable Test ●
acquisition ●

Fig. 10. TestDrive GUI for multiple random test applications

The waveforms for each test are displayed in real-time with the model under test. The interface is open and flexible, enabling any model signal to be removed or applied at any time during the simulation. In the example of Fig. 10, a list of available signals is found on the left side of the GUI.

All waveform data is stored in a database with its corresponding test ID and parameters. This information is also displayed in real-time on the TestDrive GUI. The user fault selection and sequencing is done using a Python API script, which is executed within the TestDrive GUI.

C. *Event Sequencing Using Python API*

Multiple test contingencies and possible network configurations require the use of effective test managing software for optimization and Monte-Carlo type of studies. The eMEGAsim is an open simulator which provides the user with a special Python API, object-oriented programming language, with specific built-in methods and functions that will act directly on the model in use.

For the featured application, for instance, the test activation is controlled via a Python script and programmed using the following command lines:

```
Set("Enable Test", 1)
        Wait(500)
        Set("Enable Test", 0)
```

A test with a total duration of 500 ms is enabled and stored in the database, including steady-state, fault occurrence and fault recovery observation. The use of the Python API offers a very clear syntax, intuitive object-oriented programming with the use of naturally expressed and procedural code.

D. *Real-Time and Accelerated Simulation*

The eMEGAsim target computer runs with the QNX® Neutrino® real-time operating system, which is widely used in mission-critical applications such as medical instrumentation and air traffic control. This greatly optimizes the sturdiness of the eMEGAsim simulator and greatly increases its efficiency due to direct utilization of the efficient cache subsystem of the Intel® Core™2 Quad processor chips.

The real-time simulation solution allows not only faster prototyping but also faster production of results for long term simulation in network planning and analysis. Moreover, depending on the model complexity, it may be possible to exploit the idle calculation time between steps for online accelerated simulation when HIL is not required. With enhanced computational resources for solving large detailed dynamic systems, the perspective of real-time or accelerated simulation gives profit to the use of detailed electromagnetic transients modeling for system analysis using Monte-Carlo type of studies.

VII. CONCLUSIONS

Modern power systems are evolving with new constraints to be evaluated. Major studies will require the use of very fast, flexible and scalable real-time simulators. This paper has presented an open real-time simulator capable of simulating slow and fast transients of very large power systems.

An outstanding new feature which allows for the real-time simulation of EMTP-RV models in real-time was described. The usage of a new conversion interface between models built with EMTP-RV to the SPS\Simulink environment was tested and demonstrated through numerical solver comparisons with both a simple electric circuit and a very large power system model. The results have shown very good agreement between waveforms obtained with the different simulation tools, at different fixed sampling rates. Discussion was also undertaken on the importance of choosing the right step-size suitable for the type of study conducted, which is an applicable observation with any simulation platform, either in off-line or real-time mode.

A simple application for fast Monte-Carlo studies using the featured simulator either in real-time or accelerated simulation modes has also been presented and discussed. Future studies and publications will include the demonstration of the use of these tools with a very large network model to achieve multiple random testing for protection coordination.

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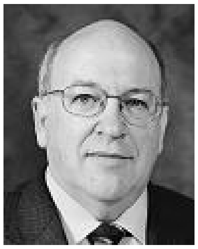
IX. BIOGRAPHIES

Jean Bélanger is the president, CEO and founder of Opal-RT Technologies, Inc. He is a specialist in real-time simulations, with more than 25 years of experience, 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.



Dr. Laurence A. Snider graduated from McGill University with a degree in Electrical Engineering, and completed his M.Sc. and Ph.D. degrees at the University of Birmingham, England. He has an extensive background in electric utility research and was one of the founders of the simulation complex of the Hydro Quebec Research Institute. He retired recently as Visiting Professor in the Electrical Engineering & Computer Science Department of Tulane University. His interests lie in real-time power system simulation, high voltage engineering, and computer applications in teaching. He is a Senior Member of the IEEE, a Fellow of the Institution of Electrical Engineers, U.K., and a Fellow of the Hong Kong Institute of Engineers.

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