Today's Power System Simulation Challenge: High-performance, Scalable, Upgradable and Affordable COTS-Based Real-Time Digital Simulators

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Abstract- **Power electronic converters have evolved rapidly, both in terms of available electronic switching devices & converter topologies. The evolutions from thyristor-based 12-pulse converters to Voltage Source Converters (VSCs) to Modular Multilevel Converters (MMCs) have placed increasingly onerous demands on simulation technology, in particular real-time digital simulators. The relatively high carrier frequencies in PWM-based converters require time-steps in the range of 10 to 50 µs, typical of what may be achieved using standard INTEL/AMD multi-core processors. Today's MMC converters add to the challenge through large number of I/Os required to monitor the voltages of a large number of cells & to individually control a very large number of IGBT switches. In this paper the evolution of modern real-time digital power-system simulator is presented – the hardware/ software challenges & solutions, leading to development of a commercially available a COTS-based simulator. Its efficacy with a simulation of an MMC-based back-to-back HVDC bipolar interconnecting two AC networks is presented. Such AC-DC-AC converter system presents challenges in terms of both the requirement of a small time step, as well as a very large number if I/O channels.**

***Index Terms*—VSC, MMC, IGBT, HVDC, FPGA, HIL, Power Quality, Real-Time Simulation**

I. INTRODUCTION

SIMULATOR technology has evolved from physical/analogue simulators (HVDC simulators, TNA's) for electromagnetic transients and protection and control studies, to hybrid TNA/Analog/Digital simulators with the capability of studying electro-mechanical transient behavior [1], to fully digital real-time simulators. Today's global power system infrastructure is rapidly changing towards increasingly distributed generation/distribution systems, and this transformation mandates expanded use of power electronic devices: HVDC, FACTS and interfacing devices for DC and variable-frequency power sources (photovoltaic, wind generation).

Real-time simulation has evolved from DSP-based boards for use in hardware-in-the-loop (HIL) testing [2] to supercomputer-based simulators such as Hydro Quebec's HYPERSIM [3], [4]. However the limitations of using proprietary hardware, such as high cost and, more importantly, the virtual infeasibility of upgrading to new technology to meet the challenges of simulating increasingly complex systems, were soon recognized. Research has been ongoing at universities and research centers towards the development of fully digital real-time simulators based on off-the-shelf PC technology, however such development was very challenging owing to the lack of suitable and affordable fast processor and inter-computer communication links. However, the advent of low-cost, easily obtainable and affordable multi-core processors[5] (INTEL or AMD) and related Commercial-Off-The-Shelf (COTS) inter-computer low-latency communication links has cleared the way for the development of much lower cost and easily upgradable real-time simulators. In fact, today's computer boards with 8 processor cores provide greater performance than 24-CPU supercomputers that were available only 10 years ago. The availability of this high performance processor technology has also reduced the need to cluster multiple PCs to conduct complex parallel simulation, thereby reducing dependence on high-end fast inter-computer communication technology. However, fast PCI Express COTS communication fabrics are now standard enabling implementation of very large real-time computer cluster suitable for the simulation of electromagnetic transients.

Modern COTS-based 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

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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, DYMOLA and AMEsim. The integration of multi-domain simulation tools with electrical simulators enables the analysis of interactions between electrical, power electronic, mechanical and fluid dynamic systems.

In this paper the evolution of modern real-time digital power-system simulator is presented – the hardware and software challenges and solutions, leading to the development of a commercially available COTS-based simulator. The efficacy of the simulator is demonstrated with a simulation of an MMC-based back-to-back HVDC bipolar interconnecting two AC networks is presented. Such AC-DC-AC converter systems, which presents challenges if terms of the requirement of a small time step, as well as a very large number if I/O channels, can be used, for example, for low-voltage converters used in the integration of distributed generation systems such as wind farms and in high-voltage system interconnections.

II. The Simulation Challenges

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. *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. *Necessity of 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 [4]. 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 1 to 2µs 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. *Large Numbers of I/Os and Switches:*

Modular Multilevel Converters (MMC) with several tens of cells per arm, with each cell having two power switches with anti-parallel diodes and a capacitor require some hundreds of I/Os linking the converters and controllers; the capacitor voltage of each cell must be fed from converter to controller, and firing signals must be fed (through opto-couplers) from the controller to the switching devices of the converter. This places very large demands on the hardware, capable of dealing with the inherent communication delays, concomitant with the requirement for small time steps, while maintaining sufficient precision of the control signals to the switching devices.

E. 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 simplified 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. 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 12 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, implementing real-time interpolation features to take into account IGBT firing events occurring between simulation time step have been used for several years by major hybrid vehicle and power electronic system manufacturers[14].

C. ARTEMiS Order-5 Real-Time Solver to Increase accuracy:

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. SSN Two-Step Solver for Micro-Grid and Distribution Systems with Small Lines:

The real-time simulation of micro-grid and distribution networks poses an additional challenge to real-time simulation since many lines are very short with transport delays much smaller than achievable time steps. A new method, called State-Space-Nodal [10] to enable the parallel and real-time simulation of systems with very short lines without adding artificial delay, thus increasing simulation accuracy with respect to the traditional technique of adding a line with a one-step delay.

E. eMEGAsim and EMTP-RT:

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 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.

IV. Modular Multilevel Converter Topology

The converter topology presented in Figure 1 is the modular multilevel converter (MMC) [9]. The system comprises an HVDC converter system, equipped with two 60-level Modular Multilevel Converters (MMC). Each converter has 60 cells per arm, with each cell having two power switches with anti-parallel diodes and one capacitor. This topology requires some 720 I/Os linking the converter and controller on one side only; the capacitor voltage of each cell must be fed from converter to controller, and firing signals must be fed (through opto-couplers) from the controller to the switching devices of the converter.

Real-time model:

The set up used for the study is presented in the Figure 2. Real time simulation with Hardware-in-the-Loop (HIL) was achieved in full numerical mode with using two real-time computers connected by analog and I/O lines. Notwithstanding the onerous requirements, real-time simulation was achieved with a time step of 25µs on standard dual six-core PC platforms using only 9 INTEL 3.2-Ghz processor cores. The simulation software is based on MATLAB, SIMULINK, SimPowerSystems and eMEGAsim.

In HIL mode, two real-time computers are used to simulate the plant (Target 1) and the controller (Target 2) and are interfaced with 180 analog and 180 discrete I/O signals. The controller of the right-side HVDC converter is simulated in the Target 2 computer while the controller of the left-side converter is simulated in the Target 1 computer together with the plant model. Figure 2 also shows how the model is separated for parallel simulation on nine (9) processor cores of the 12-core computers. All processor cores are interfaced by high-speed on-chip and on-board shared memory. Seven processors are used for the MMC systems while one processor is used for the controller and one processor is used for the AC network model.

The same setup is used for fully numerical simulation mode except that the controller of the right-side converter is also simulated in a separate processor core of the Target 1 computer. In this case, the communication between the controller and the plant model is made through shared memory instead of I/O converters.

Comparing Results with Reference Case made with One us Time Step

The results obtained with OPAL-RT real-time models are compared with those obtained from a reference non-real-time model which uses a 1µs time-step. The reference model, called the SPS model, uses the same configuration and parameters as the OPAL-RT real-time models, and uses the universal converter bridge model from the SimPowerSystems (SPS) library. Note that while the standard universal bridge model is very accurate, it cannot be used in real-time simulation since its state-space matrices must be continuously recomputed during the simulation, and this leads to very lengthy and

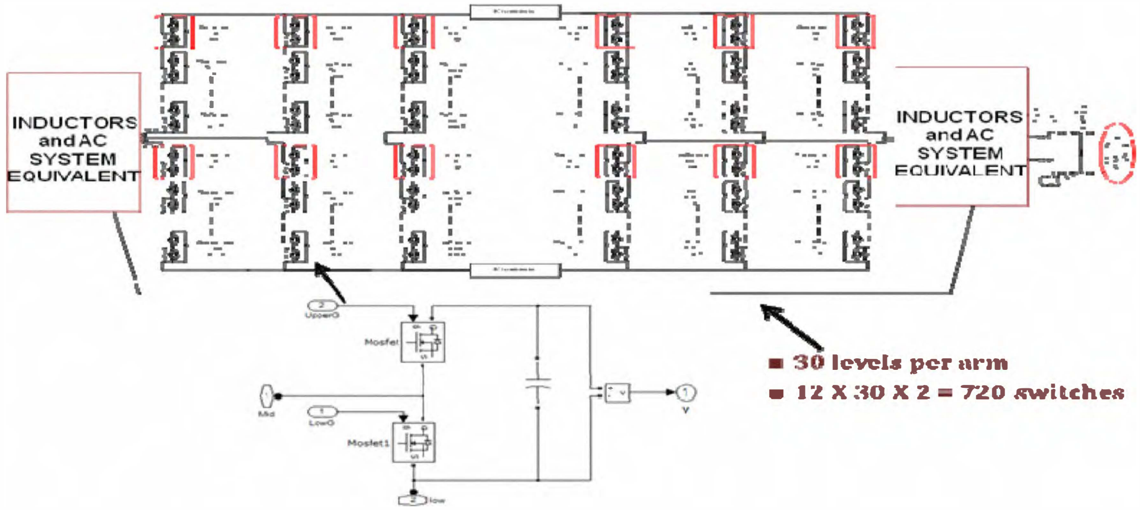

Fig. 1. Modular Multilevel Converter Topology.

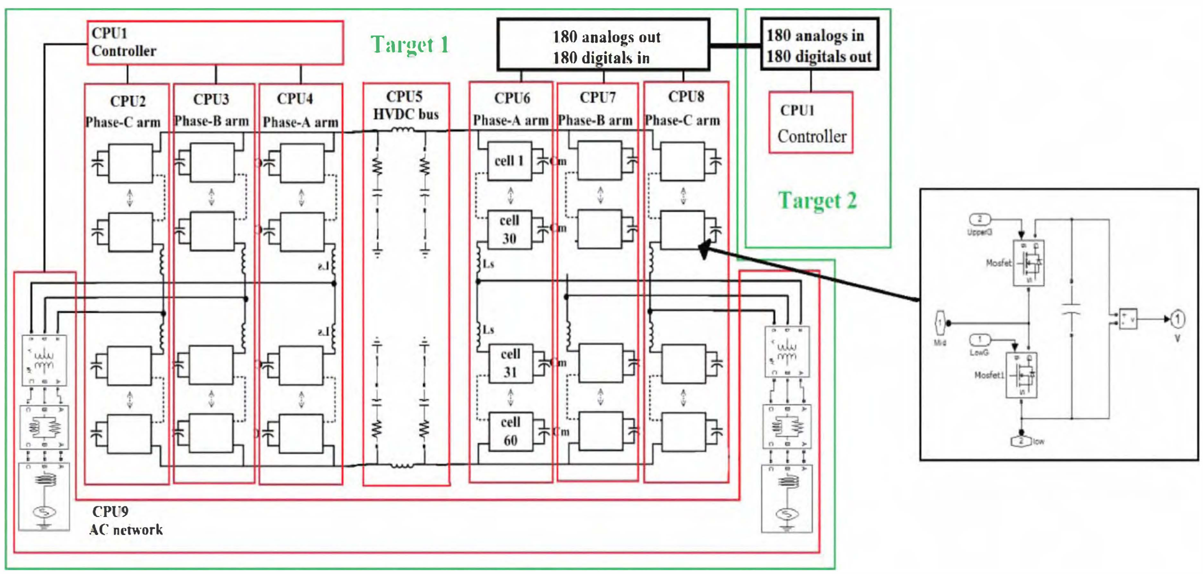

Fig. 2. Real-Time Simulator configuration & model distribution for HIL test.

non-constant processing times. Furthermore, the SPS universal bridge model does not simulate the effects of firing events occurring within the model simulation step since SPS uses a very accurate variable-step solver, iterating at each switching event – clearly not suitable for real-time solution. Consequently, the OPAL-RT real-time model uses the SPS standard model library for transformers, inductors, resistors and capacitor, and the OPAL-RT MMC cell model with Opal-RT's ARTEMiS solver, which is optimised for real-time simulation with a time-step in the range of 20 and 50 µs.

The Controllers

The controllers used for the static converter can regulate the voltage of the capacitor cell, but the amplitude and the angle of the PWM reference voltages must be set manually for the purpose of these tests. Opal-RT's RT-Events control block library is also used for accurate generation of firing pulses occurring within the model's time-step.

While this is a very simple controller, it is adequate for testing the plant model under a number of balanced and unbalanced steady-state and fault conditions. (It must be noted that the objective of this study is to evaluate the feasibility and performance of the simulator and not to develop a controller).

V. Simulation Results

A. Natural rectification mode – Fully Numerical Mode – 20 µs:

Figure 3 presents results obtained with the proposed real-time model using a time-step of 20 µs, superimposed with the results obtained with SPS at 1µs where the system operates in natural rectification mode during the charging phase. As shown in Figure 1, there is only a small difference, around 0.015 p.u., between the SPS and Opal models, which is acceptable for real-time HIL tests, The Figure 3 verifies the capacitor voltages from all the cells for both model in natural rectification mode. One can see that results are very close.

B. Steady-State Results – Fully Numerical Mode – 20 µs:

The Figure 4 presents results obtained with the proposed model using a time step of 20 µs, superimposed with the results obtained with SPS with a time step of 1 µs, when the system operates in the controlled mode during the steady-state phase. The error is less 0.025 p.u. between the real-time 20 µs model and the 1 µs model.

C. Fault Condition – Fully Numerical Mode – 20 µs:

Different faults were applied to the model to test its accuracy during transient conditions. The Figure 5 presents the results for a fault applied between phase A and the ground at the location between the AC power supply and the power transformer. The HVDC bus voltages and currents are shown. Results obtained with the real-time model running at 20 µs compare very well with results from the model running at 1 µs, with the error ranging between 0.02 p.u. and 0.1 p.u.

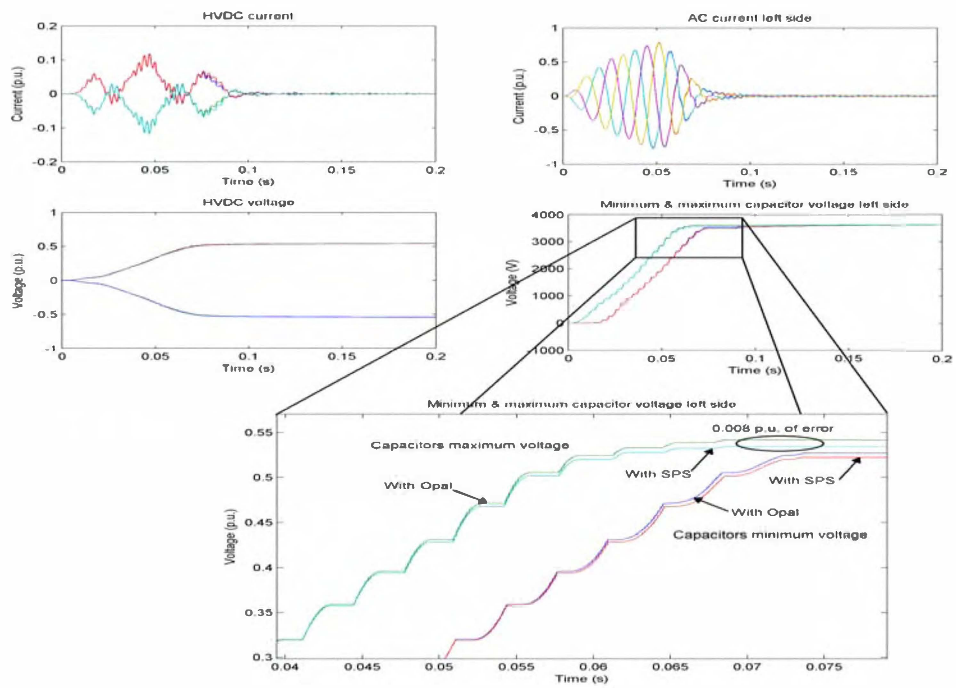

Fig. 3. Natural rectifying mode- SPS and Opal model results superimposed.

D. Tests in HIL Mode

The same tests were repeated in the HIL mode using two real-time digital simulators: one for the plant and one for the controller. Both simulators (Target 1 and Target 2) are interconnected only through their respective I/O systems, as illustrated in the Figure 6. A total of 360 analog and digital signals with time stamping are used in each real-time computer, which requires a very high performance I/O system, only available with high-end simulators. The controller is synchronized with the AC voltage using a phase-lock-loop consistent with real systems.

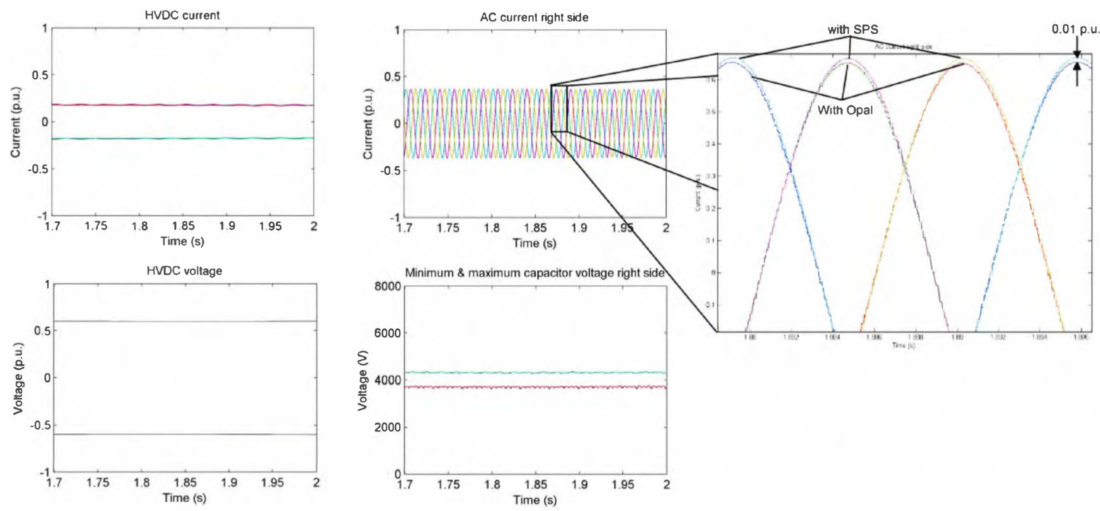

Fig. 4. Steady state for HVDC bus at 0.6 p.u – SPS and Opal model results superimposed.

The I/O communication delays obtained with the real-controller impact the power flow, while the ideal controller would not include these delays. This explains the lower current on the HVDC bus. However, the voltage of the HVDC bus is still regulated by the internal controller, and will follow the reference of 1 p.u.

The Figure 7 illustrates the usefulness of HIL testing to analyse phenomena that are often not seen with ideal controllers. A future study will analyse the behaviour of the systems under fault conditions.

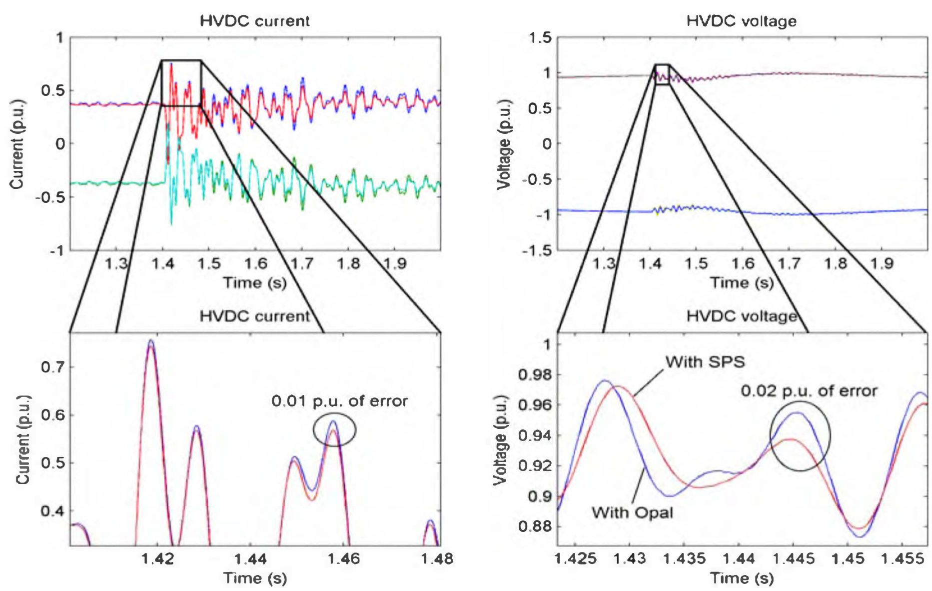

Fig. 5. HVDC current and voltage and their error, test FT-2. SPS and Opal model results superimposed.

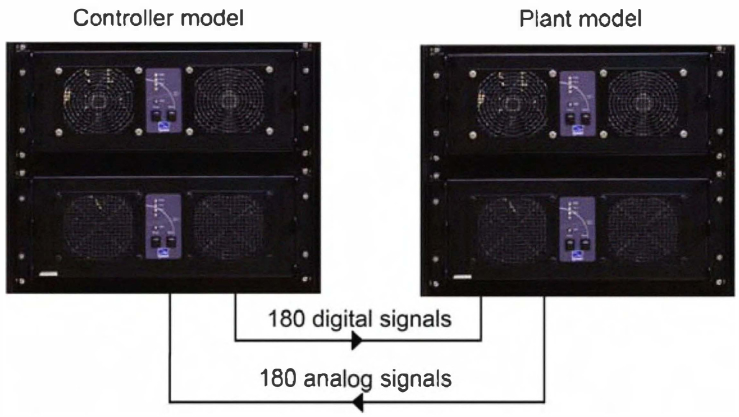

Fig. 6. HIL setup using two targets with extra IO expansion box.

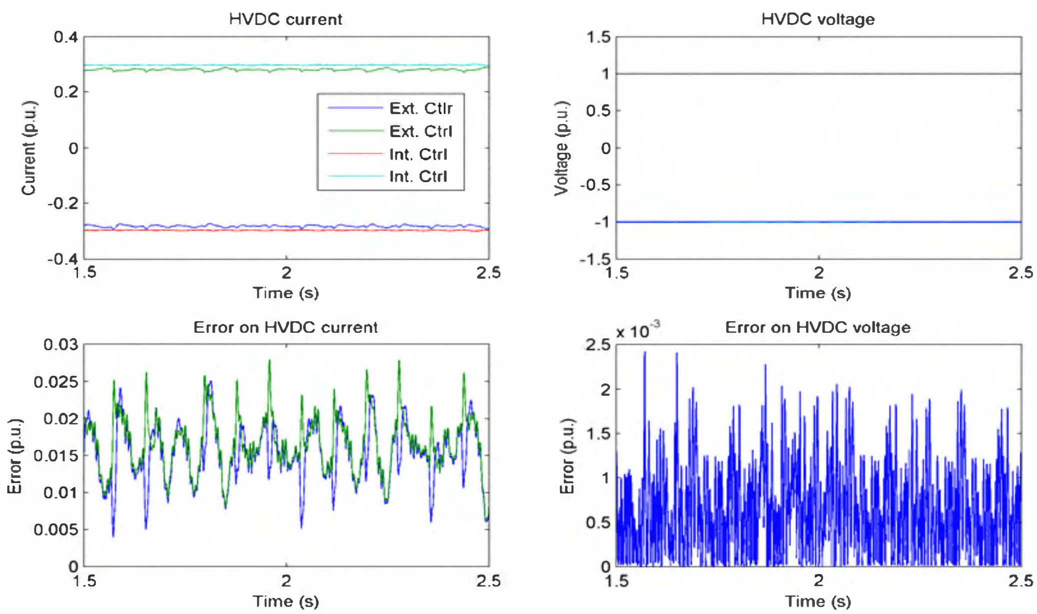

Fig. 7. HVDC current and voltage and their error, using external controller.

E. Simulation Performance:

TABLE 1
Real time simulation's timing performance

CPU frequency3.3 GHz				
Cpu	subsystem	T_s (µs)	T_{cal} (µs)	$T_{s\ min}$ (µs)
1	Ac grid	20	2	
2	Arm-A left	20	3	
3	Arm-B left	20	3	
4	Arm-C left	20	3	
5	Arm-A right	20	3	
6	Arm-B right	20	3	11
7	Arm-C right	20	3	
8	Dc link	20	1	
9	PWM gen left	20	5.4	
10	PWM gen right	20	5.4	
11	controller	20*5	3.8	

In order to minimize calculation time to allow real-time simulation, the model is distributed across 11 CPU cores. Table 1 illustrates the calculation times achieved on each CPU core during real time simulation. T_s is the time step used during simulation, T_{cal} is the time required for calculation of each subsystem, and $T_{s\ min}$ is the minimum time-step that can be achieved. T_s appears much larger then $T_{s\ min}$; this is due to communication latency between subsystems. When physical I/Os are added, the minimum achievable time-step while managing over 360 I/Os is only 20µs.

Table 2 shows time timing performance if additional subsystems are merged together, for two CPU frequencies. This demonstrates the advantage of using multiple CPUs to reduce $T_{s\ min}$.

The HIL tests presented above were made with only 180 I/O channels. However in practice the number of I/O channels can easily reach 2000. Consequently, we evaluated the time required to transfer a large amount of I/O data from- and to- the main processor memory.

TABLE 2
Timing performance on 6 CPUs

		CPU frq=3.33G		CPU frq=2.4G	
CPU	subsystem	Tcal (us)	T_s min (us)	Tcal (us)	$T_{s\ min}$ (us)
1	Ctrl, ac dc	6		9	
2	Arms A, B, left side	7		10	
3	Arms A, B, right side	7		10	
4	Arms C left & right side	7		10	
5	PWM gen left	9		12	
6	PWM gen right	9	13	12	19

The eMEGAsim I/O simulator can include several I/O subsystems interfaced with the processor boards using PCI Express. Each I/O subsystem includes one FPGA board controlling up to 128 analog I/O converter or 256 discrete I/O channels. The PCI Express communication fabric now installed on all modern PCs uses a high-speed switch capable of transferring data directly to and from processor memory at speed exceeding 10Gbits per second. In fact, the new generation of PCI express switches can reach speeds exceeding 40Gbits. Tests have demonstrated that more than 1600 IO channels can be transferred back and forth (round trip) to one PC in less than 16 microseconds. More than 3200 IO channels can be transferred using two 12-core PCs for larger models. Such performance, achieved by standard off-the-shelf affordable technology cannot easily be reached by custom made simulators using 5-year old technologies.

VI. Conclusions

With today's technology, the challenges of providing a comprehensive simulation tool using standard PCs and COTS components has been achieved. While conventional 12-pulse HVDC systems, which are still in used to transport large amounts of power over very long distances, were one of the principal motivators for the development of digital real-time simulators, simulation of such systems, even with a time step as large as 50 microseconds, was a challenge even for supercomputers or custom-made real-time digital simulators. Today, however, even multi-terminal HVDC systems can be simulated in real time with a time step as low as 10 microseconds, using eMEGAsim simulators equipped with standard INTEL 3.2-GHz multi-core computers. Using such low time step increases, for example, the simulation accuracy of fast transients occurring on the DC side of converters; urthermore, the addition of FPGA technology solves the communication delay problems, and today thousands of I/O channels, a requirement for simulation of MMC converters, can be accommodated. The simulation of an MMC converter on an eMEGAsim using a time step of 20µs and with the number of I/Os exceeding 360 channels demonstrated sufficiently accuracy for control development, design and tests in HIL applications. If needed, more accurate results could be obtained using a smaller time step and with the use of FPGA processors.

In this paper application of today's simulation technology was demonstrated with the simulation of an MMC converter on an eMEGAsim using a time step of 20µs and with the number of I/Os exceeding 360 channels. Sufficient accuracy for control development, design and tests in HIL applications was achieved, and, If needed, more accurate results could be obtained using a smaller time step and with the use of FPGA processors. Furthermore, the simulator can be used to simulate a complete system, including the controller in off-line mode, at a speed faster than real time and with an acceleration factor of more than 200 times as compared to simulations made on only one processor at a time step of 1µs.

With today's readily available COTS technology small time steps and a very large number of I/O channels can be accommodated: for example more than 3200 IO channels can be transferred using only two 12-core PCs. Such performance is not achievable by the custom made computers or supercomputers using 5-year old technologies, and would require manufacturers to engineer new custom technology and a very high cost.

VII. References

[1] 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.

[2] Kuffel R., J. Giesbrecht, T. Maguire, R.P.Wierckx, P. McLaren. 1995. "RTDS – a fully digital power system simulator operating in real time", in *Proc. 1995 IEEE International Conference on Digital Power System Simulators*, pp. 19-24, April 5-7, 1995, Texas, USA.

[3] V.Q. Do, J.C. Soumagne, G. Sybille, G. Turmel, P. Giroux, G. Cloutier, S. Poulin, "Hypersim, An Integrated Real-Time Simulator for Power Network And Control Systems", Third International Conference On 10 Digital Power System simulators (ICDS 99), Vasteras, Sweden, May 25-28, 1999.

[4] Dufour, C.; Abourida, S.; Belanger, J.; , "Hardware-In-the-Loop Simulation of Power Drives with RT-LAB," Power Electronics and Drives Systems, 2005. PEDS 2005. International Conference on , vol.2, no., pp. 1646- 1651, 28-01 Nov. 2005.

[5] .M. Ramanathan, "Intel Multi-Core Processors: Making the Move to Quad-Core and Beyond", White Paper [Online]. Available: http://www.pogolinux.com/learn/files/quad-core-06.pdf.

[6] J. Bélanger, V. Lapointe, C. Dufour, L. Schoen, "eMEGAsim: An Open High-Performance Distributed Real-Time Power Grid Simulator. Architecture and Specification" in *Proceedings of the International Conference on Power Systems (ICPS 2007)*, December 12-24, 2007, Bangalore, India.

[7] J.F. Cécile, L. Schoen, V. Lapointe, A. Abreu, J. Bélanger, "A Distributed Real-Time Framework For Dynamic Management of Heterogeneous Co-Simulations" [Online]. Available: http://www.rtlab.com/files/scs_article.pdf

[8] H. Jones, "Return on Investment in Simulink for Electronic System Design", White Paper [Online]. Available:

http://www.mathworks.com/mason/tag/proxy.html?dataid=5872&fileid=24121.

[9] W. Li, G. Joós and J. Belanger, "Real-time simulation of a wind turbine generator coupled with a battery supercapacitor energy storage system," *IEEE Trans. Industrial Electronics*, Vol. 57, Issue 4, pp. 1137-1145, 2010.

[10] C. Dufour1, J. Mahseredjian, J. Bélanger1, J. L. Naredo, "An Advanced Real-Time Electro-Magnetic Simulator for Power Systems with a Simultaneous State-Space Nodal Solver", IEEE/PES T&D 2010 - Latin America, São Paulo, Brazil.

[11] C. Dufour, J. Bélanger, S. Abourida, "Real-Time Simulation of Onboard Generation and Distribution Power Systems," in *Proceedings of the 8th International Conference on Modeling and Simulation of Electrical Machines, Converters and Systems (ELECTRIMACS 2005)*, April 17-20, 2005, Hammamet, Tunisia.

[12] C. Dufour, S. Abourida, J. Bélanger, V. Lapointe, "InfiniBand-Based Real-Time Simulation of HVDC, STATCOM, and SVC Devices with Commercial-Off-The-Shelf PCs and FPGAs", in *Proc. 2006, IEEE Industrial Electronics Society*, Paris, France, November 7-10, 2006, pp. 5325-5331.

[13] J. Pan, R. Nuqui, K. Srivastava, T. Jonsson, P. Holmberg, Y.-J. Hafner, "AC Grid with Embedded VSC-HVDC for Secure and Efficient Power Delivery", *IEEE Energy 2030 Conference (2008)*, Atlanta (GA), USA, November 17-18, 2008, pp. 1-6.

[14] 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.

[15] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian, L. Gérin-Lajoie, "On a New Approach for the Simulation of Transients in Power Systems," *Proceedings of the International Conference on Power Systems Transients (IPST 2005)*, Montréal, Canada, June 19-23, 2005.

[16] J. Mahseredjian, "Simulation des transitoires électromagnétiques dans les réseaux électriques", *Édition Les Techniques de l'Ingénieur*, Dossier n°D4130, 2008.

[17] H.W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single and Multi-Phase Networks," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-88, no. 4, pp. 388-398, 1969.

[18] 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.

VIII. 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 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.

Dr. Laurence Snider was born in Montreal, Quebec, Canada. He 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 presently is a visiting Professor in the University of Guadalajara, Mexico. His interests lie in real-time power system simulation, high voltage engineering, and computer applications in teaching. He is a Life Senior Member of the IEEE, and was a Fellow of the Institution of Electrical Engineers, U.K., as well as of the Hong Kong Institute of Engineers.

Girish Nanjundaiah was born in Shimoga, Karnataka, India in 1971. He graduated from the Karnataka University, Dharwad in year 1993. He has been involved with Mathematical Modeling, Simulation and Real Time Operating Systems since 1993. He started Opal-RT operations in India in 2004 and has been handling the Indian market since then, with particular emphasis on vertical markets including Automotive, Aerospace, Transportation and Electrical Engineering in Academic Circles.