Real-Time Simulation of Large-Scale Power Systems using EMTP-RV and Simulink/SimPowerSystems

Abstract - **This paper presents a modern PC-based real-time simulator using the latest INTEL quad-core processors to simulate a relatively large power system. The performance of the simulator is evaluated by comparing the results of different contingencies in two different simulation environments. A large grid model built using the EMTP-RV software and simulated in real-time using the eMEGAsim platform's EMTP-RT software tool is described. Comparisons between the off-line and the Real-Time simulations are made using superimposed steady-state and fault condition waveforms.**

I. INTRODUCTION

Power system analysis tools have been evolving at an astonishing rate over the past few years, in line with the corresponding evolution of computing hardware. Traditionally, power system analysis, like power flow, transient stability and electromagnetic transients, has been performed on standard computing platforms, while hardware-in-the-loop (HIL) development and testing of protection and control hardware has been performed on Transient Network Analyzers (TNA) and, more recently, real-time fully digital simulators. With today's technology, it is now possible for the same computer hardware to be used for HIL applications, off-line simulation using commercial simulation tools for electromagnetic transients such as EMTP-RV, SimPowerSystems, PSCAD and NETOMAC, and transient stability analysis with tools such as PSSe, Eurostag and DigSilent.

Some of these applications can now interact, providing the basis for the development of a high-bandwidth, comprehensive hybrid simulation tool for use on a single scalable hardware platform. Such a tool can cover the range of studies from fast electromagnetic transients to voltage stability studies. Parallel processing, coupled with sophisticated software that uses interpolation techniques, provides remarkable speed improvements for real-time simulation of large systems that incorporate power electronic devices, modeled at the device level. Faster than real-time simulation, for applications such as contingency analysis in dynamic security studies, is also feasible using the same Commercial off-the-shelf (COTS) hardware components.

The use of readily available multi-core processors and COTS computer components in the integration of real-time simulators has significantly decreased costs in comparison to custom-made digital simulators and supercomputer-based simulators. For the past several years, COTS-based high-end real-time simulators using standard multi-processor computers have been available for use in aerospace, robotic, automotive and power electronic system design and testing, and are now available for the simulation of large-scale power system grids,

micro-grids, wind farms and power systems installed in large electrical ships and aircrafts. Because of their capability to simulate such complex systems using integrated third-party open and multi-domain software tools, COTS-based real-time simulators represent the most advanced engineering tools available today for the analysis of interactions between electrical, power electronic, mechanical and fluid dynamic systems.

This paper discusses the simulation challenges facing power system engineers dealing with large-scale power systems with integrated power-electronic devices and control systems. Results obtained with a PC-based eMEGAsim real-time simulator [1] using the latest INTEL quad-core processors to simulate a relatively large power grid will be presented and compared with results obtained with the well known EMTP-RV [7][8][9] off-line simulation tool.

II. MULTI DOMAIN ENGINEERING, RAPID CONTROL PROTOTYPING AND FULL REAL-TIME SIMULATION

IGBT-based power converters, which have expanded in use for power grid applications (e.g. distributed generation, or DG), require a wide range of analyses and the involvement of engineers from different specialized fields. For instance, engineering studies are needed to measure the impact that the interconnection of DGs will have on specific. Moreover, during the analysis and design process of DG integration projects, hardware design engineers may want to test the effectiveness of controllers, as well as their effect on complex power system models. The use of real-time simulators during two different design phases is illustrated in Fig. 1. Rapid Control Prototyping using hardware-in-the-loop (HIL) is a classic application of real-time simulators. HIL is fast becoming the only solution for testing complex controllers used in large power systems, for obvious practical and economical reasons. This is compared to the use of analog test benches or conducting tests during commissioning A variety of normal operation and fault conditions can be easily reproduced using a plant model; conditions that would be costly and dangerous to create on a physical plant. Moreover, HIL tests combined with the Model-Based Design practice is the most cost-effective option for use in the design and test of large power system controllers. The Model-Based Design and HIL approach enables the dynamic behavior of a large network to be easily represented in a non-destructive manner. However, detailed models created using advanced modeling software, such as SimPowerSystems/Simulink and EMTP-RV, are required during HIL testing to achieve results as near as possible to real world physics, further requiring the use of very powerful real-time simulators.
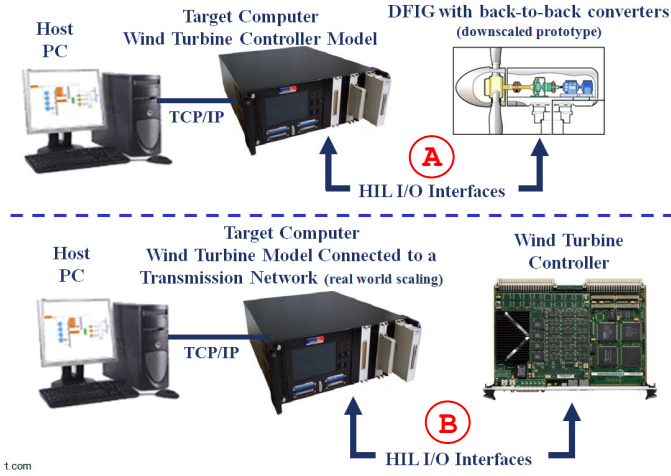
Fig. 1. Real-Time simulation in various design phases: A) Model-Based Design B) Rapid Control Prototyping

System planning engineers use detailed electromagnetic transient models because of their flexibility and resemblance to reality. Average models may also be used to reduce processing time, but their use may be time consuming when adaptation is needed to conduct different studies. For example, since advanced mathematical modeling experience may be needed for the creation of particular models, developing an average model for the study of power quality aspects during unbalanced conditions may require experts not always readily available to small companies involved in DG development. The use of standard simulation tools such as SimPowerSystems/Simulink and EMTP-RV, which allow easy and fast detailed modeling, permits simultaneous study of different aspects such as protection coordination, power quality, stability analysis, control interaction studies, and control prototyping.

It is interesting to note that implementing a detailed model may be easier than implementing a simplified model. However, designing an affordable simulator capable of using detailed models for real-time simulation of large power grids equipped with a large number of power electronic systems is a challenge for suppliers and research centers involved in real-time simulator development. The next section describes the architecture of a distributed real-time simulator capable of meeting these challenges through the use of standard PC hardware and software.

III. SIMULATION ENVIRONMENTS

A. SimPowerSystems/Simulink

Simulink has emerged as the worldwide standard for scientific computing and simulation of electro-mechanical systems used in the aerospace and automotive industries. It achieves real-time performance through the use of the popular Real-Time Workshop C-Code generator [4]. SimPowerSystems (SPS) [2], developed and supported by Hydro-Quebec Research Center (IREQ), is a Simulink toolbox for the simulation of power systems and machine drives. SPS

provides a drag-and-drop visual graphic environment with multiple model components, all based on electromechanical and electromagnetic equations. [3]. Both Simulink and SPS are available as part of the MATLAB software for mathematical processing. By using the toolboxes included in this multifunctional software, the user can easily model any power system device and control, as well as all mechanical subsystems.

B. SimPowerSystems/Simulink on eMEGAsim

Simulink and SimPowerSystems have also been adapted for use in real-time simulation of large power systems through the use of solvers optimized for real-time simulation of electrical networks, such as ARTEMiS [5], and real-time distributed software platforms, such as RT-LAB. eMEGAsim also integrates RT-EVENTS, a toolbox specifically optimized for real-time simulation of power electronic drive models and controllers. All of the above tools have been successfully used for several years by major hybrid vehicle and power electronic system manufacturers [6].

C. ARTEMiS Real-Time Solver

The ARTEMiS 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. It also includes a set of special discrete solvers based on 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 [3][5].

D. EMTP-RV for Off-Line Simulation

EMTP-RV is a revised version of the well-known ElectroMagnetic Transient Program, first developed in the late 1960s, and widely considered today to be the industry standard tool for off-line simulation by many power system specialists. EMTP-RV provides a user-friendly graphical interface, called EMTPWorks, to construct and edit large one-line circuit diagrams that allow detailed modeling of network components including control, linear and non-linear elements [7][8].

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 [9]. It uses the trapezoidal numerical integration technique as well as the backward Euler method to solve the system's equations.

As with SPS/Simulink, EMTP-RV can simulate controls and power devices using detailed models for time-domain electromagnetic transient analysis. Average models, fundamental frequency load-flow and impedance frequency scan solution are also supported. This set of tools, developed by universities and research centers associated with major utilities such as EDF and Hydro-Quebec, is certainly an asset to the power system industry.

E. eMEGAsim and EMTP-RT

The demands of EMTP-RV users for faster and real-time simulation exploiting modern multi-core processors and

clusters has lead to its integration with eMEGAsim. As a result, the EMTP-RT software interface has been developed to seamlessly integrate key eMEGAsim features into the modeling environment of EMTP-RV. These include real-time simulation capabilities, the ability to separate models for execution on multiple processor cores, and full integration with both SPS/Simulink and existing eMEGAsim toolboxes optimized for power electronic system simulation, as illustrated on Fig. 2.
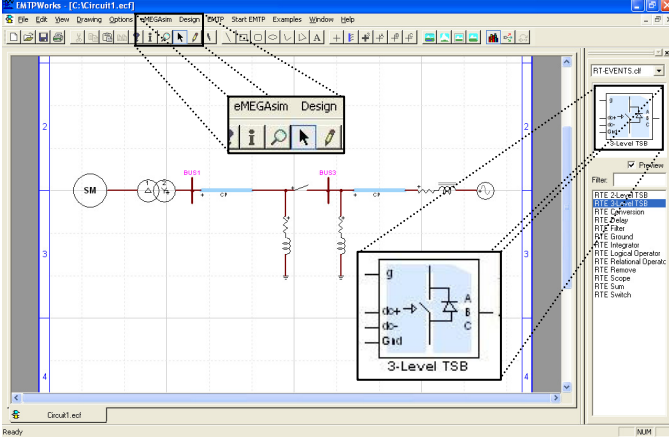

Fig. 2. EMTPWorks and the integration of EMTP-RT combined with special component libraries.

EMTP-RT enables automatic conversion of an EMTP-RV model to an SPS/Simulink model, including data transfer, data conversion and model compilation. This process occurs by clicking on the eMEGAsim menu item within EMTPWorks, as illustrated on Fig. 2, and is achieved automatically within seconds without the need for user intervention. The SPS model can then be modified using SPS/Simulink blocks and/or for off-line simulation in the MATLAB environment, as well as for real-time simulation with eMEGAsim. Additional EMTP-RT functionality, including complete automation and processor allocation, is currently under development.

EMTP-RT takes full advantage of all tools provided in EMTP-RV, including off-line Load-Flow solution and Frequency Scan analysis. It combines the power of real-time and accelerated simulation, available with eMEGAsim, the flexibility of Simulink for control design, and a variety of other toolboxes available for multi-domain simulation. Current EMTP-RV users now have the option to conduct hardware-in-the-loop testing with their EMTP-RV models without the need to migrate to unfamiliar software or to manually convert their models and data, saving them valuable time and reducing the risk of errors.

The Load-Flow and steady-state solutions obtained with EMTP-RV can be used to initialize machines and control states during real-time simulation.

IV. 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 [10]. More than 10 wind turbines with detailed AC-DC-AC power electronic converters modeled in detail were simulated in less than 50 microseconds with seven (7) processors. The large power system model depicted in Fig. 3 presents a network with a very large number of busses and 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 for use with the eMEGAsim real-time simulator.

This section describes the featured model and validates the accuracy of, and similarity between EMTP-RV and eMEGAsim (SPS/Simulink environment), by comparing results in steady-state and fault conditions with both simulation environments. The same model could be implemented directly with SPS depending on the user's preference.

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 parameter 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:

$$\tau = d\sqrt{LC} \qquad (1)$$

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.. In the studied network, some lines were sectioned 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 separated for the parallelization of the computation tasks on 7 processor cores of an 8-core eMEGAsim target standard computer. Electrical circuits were carefully distributed because the added delays, other than natural delays provided by line models, can change the dynamic behavior of the system and lead to numerical instability, creating unrealistic high-frequency oscillations not present in the actual system. This technology limitation is common to all commercially available real-time simulators. Most of the system separation was done using optimized distributed parameter lines from the ARTEMiS toolbox. Since 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
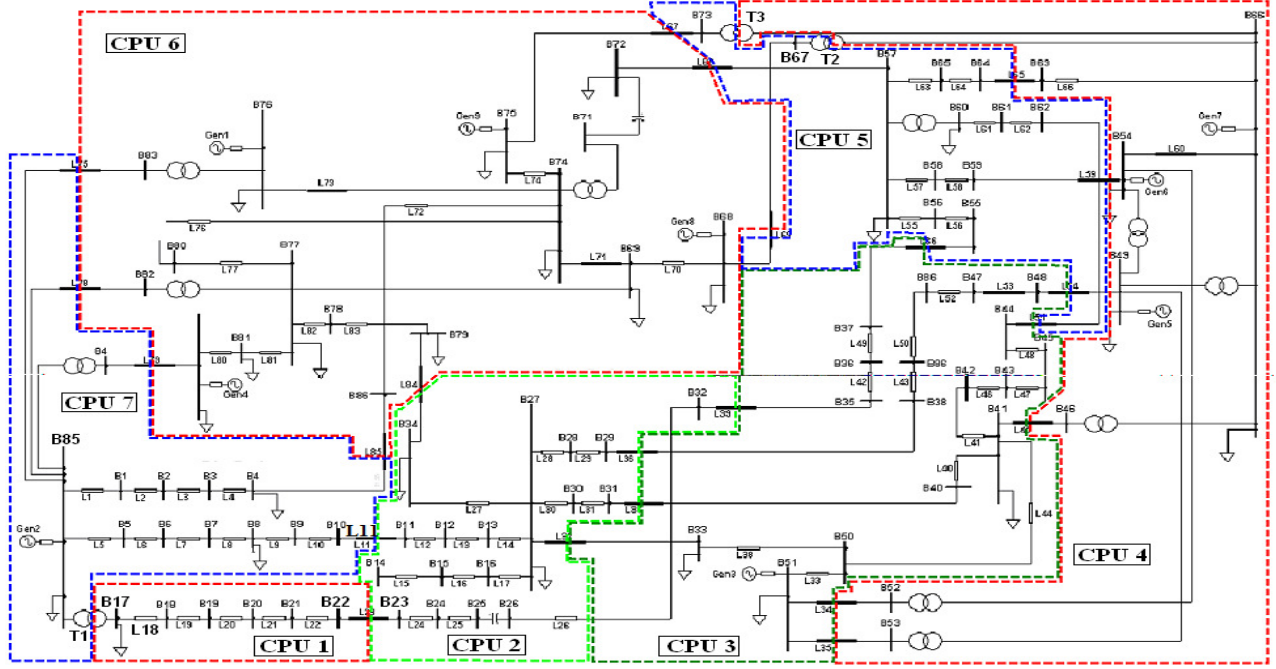
Fig. 3. Schematic diagram of the network model

(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. Distributed inductance and capacitance models, often referred to as stubline models, are widely used in real-time simulation. This is due to their similarity to distributed parameter transmission lines but with a transport delay τ of exactly one time step. With wisely chosen parameters, the stubline model will provide a very good approximation of 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

As seen in Fig 4., all of the displayed steady-state voltages match with very good agreement. Slight differences are seen at some buses as the largest difference in magnitude is of 0.002 pu and the maximum angle difference is of 1.08 degrees.

The graph comparisons of the steady-state simulation results, both with the EMTP-RV and eMEGAsim platforms, reveal an accurate match for the computation of steady-state conditions. However, the similarities of the dynamic models will be demonstrated with transient waveforms in the next section.

C. Line Energization Transients

Line L11, which is a 46 km line, thus considered a long line, is disconnected from the network at both ends of the system's steady state period. At t = 1.3163 s, the line's breakers are closed at both ends (busses 10 and 11). The waveforms for the voltage measured at bus B10 and current through line L11 are shown in Fig.6 and Fig.7.

The harmonic oscillations at the natural frequency of line L11 are simulated accurately using both simulation
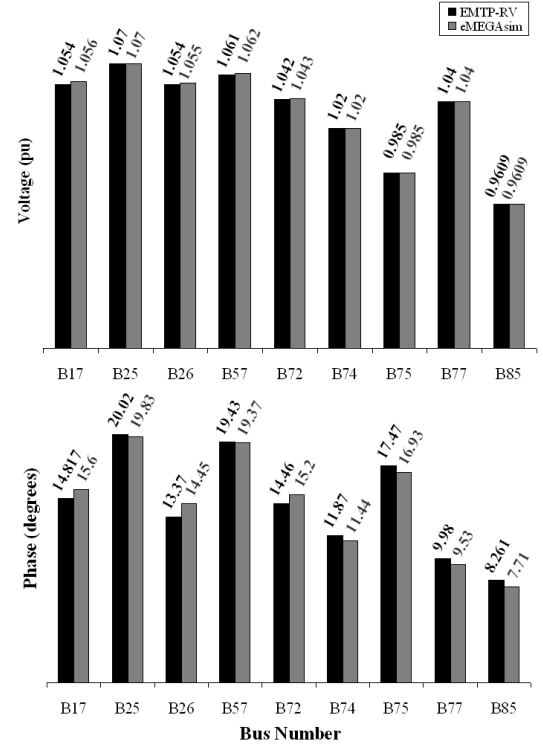

Fig. 4. Comparison of steady-state voltage at selected locations

environments. However, higher frequency flickers caused by surrounding smaller lines in the distribution grid are more pronounced in the EMTP-RV results. In fact, this small difference is apparent because of EMTP-RV's use of a half-step backward Euler integration during discontinuities. This will be discussed further in the final version of the paper.
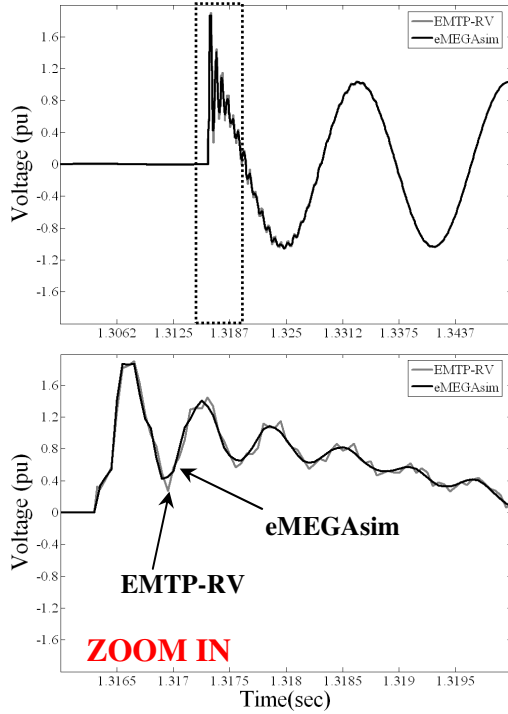
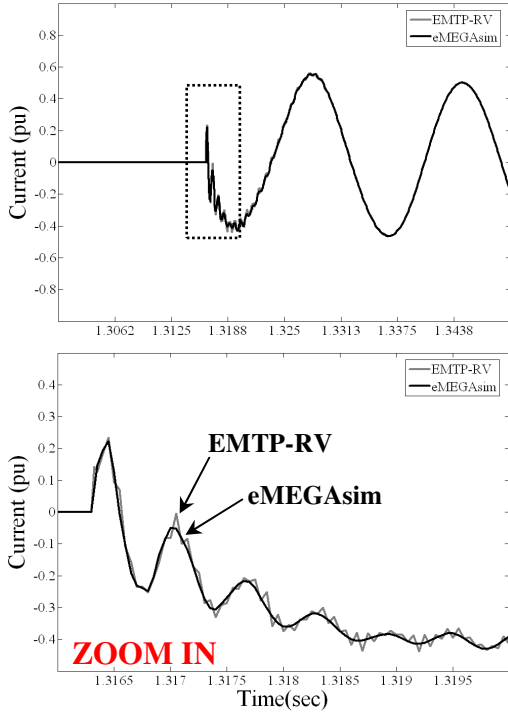Fig. 6. Phase-A Voltage at bus B10 at line connection

Fig. 7. Phase-A current through bus B10 at line connection

V. Conclusions

A new software tool is now available that enables EMTP-RV users to bring their off-line studies to real-time, enabling the use of the same graphical user interface and component data for off-line and real-time simulation, and reducing the time required to prepare a real-time simulation. Users will benefit from a sophisticated one-line diagram editor optimized for large power grids. More importantly, real-time simulation specialists will be able to verify simulation results using two different simulation solvers and to take advantage of EMTP-RV's strong reputation in the electromagnetic transient simulation field.

In the final paper, the high frequency bandwidth of the featured network model and differences between solvers will be discussed, including the use of a single fixed step algorithm in real-time simulation versus multi fixed steps, and criteria for choosing the right time-step to represent phenomena of interest. Results will show that using a state-space electrical system representation is as accurate as using a standard nodal analysis approach for electromagnetic transient simulation. Multiple random tests using the eMEGAsim platform will also introduce the reader to the accelerated simulation modes for faster than offline and faster than real-time simulation.

VI. References

[1] 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.

[2] L.-A. Dessaint, K. Al-Haddad, H. Le-Huy, G. Sybille, P. Brunelle, "A Power System Simulation Tool Based on Simulink," *IEEE Trans. On Industrial Electronics*, vol. 46, pp. 1252-1254, Dec. 1999.

[3] 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.

[4] G. Hodge, J. Ye and W. Stuart, "Multi-Target Modelling for Embedded Software Development for Automotive Applications", SAE Technical Paper Series 2004-01-0269 [Online]. Available: http://www.mathworks.com/mason/tag/proxy.html?dataid=4361&fileid=20307

[5] C. Dufour, J. Bélanger, "Discrete Time Compensation of Switching Events for Accurate Real-Time Simulation of Power Systems", in *Proc. 2001 IEEE Industrial Electronics Society Conference*, pp. 1533-1538.

[6] 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

[7] 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

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

[9] 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.

[10] 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.