Paper presented at the SC '12 Workshop: High Performance Computing, Networking Storage and Analysis (SC-12), 10-16 Nov. 2012 in Salt Lake City, Utah, USA

Real-Time Simulation using Transient Stability, ElectroMagnetic Transient and FPGA-based High-Resolution Solvers

Christian Dufour, *Member IEEE*, Vahid Jalili-Marandi, *Member, IEEE*,
Jean Bélanger, *Senior Member, IEEE,*

***Abstract*— This paper discusses recent developments of the high-performance computing techniques for the real-time simulation of power systems. Depending on the size of the network and the required resolution, different methods are used: phasor-based method for Transient Stability (TS) simulation, and ElectroMagnetic Transient (EMT) simulation. Modern, fast power-electronic devices also often require high-resolution simulation on FPGAs. The paper discusses these solvers, their commercial availability along with some benchmarks.**

***Index Terms*—Large-scale systems, power system simulation, power system transient stability, real-time simulation, FPGA.**

I. Introduction

SIMULATORS have been used extensively in the planning and design of electrical systems for decades. From the layout of transmission lines in large scale power systems to the optimization of motor drives in transportation, simulation has played a critical role in the successful development of many applications. In recent years, power system analysis and operation have also become increasingly complex for several reasons. Inclusion of renewable energy resources with intermittent and asynchronous generation and higher grid interconnection are few examples of this growing complexity. These simulators can use various type of solvers that depends on the size of the network under study and the required simulation resolution or bandwidth.

Transient Stability (TS) analysis mainly deals with the power transfer stability of large power systems. In essence, AC network power system stability depends on the synchronicity of the multiple rotating sources that compose it. During disturbances caused by faults, the generating units are subjected to angle and speed variations that could lead to loss of synchronism and system collapse.

The need for real-time transient stability simulation was highlighted by the recent black out events that occurred in North America (August 14, 2003) and Europe (November 4, 2006). According to analysis of the contributing factors to these events, real-time dynamic security assessment and system monitoring were identified as the most important issues[6][8].

Real-time Electromagnetic Transient (EMT) simulators are used for many purposes. For example, they are utilized for Hardware-In-the-Loop validation of complex power electronic power system devices, such as HVDC or STATCOM, before connecting these devices in the field [3][21][25].

This paper discusses algorithms for the real-time simulation of power systems and presents some performance results. The paper emphasizes recent advanced algorithms for both EMT and TS simulation tools usable on highly-parallel multi-processor and multi-core architectures. It also discusses new advancements in high-resolution FPGA-based real-time simulation methods [5].

The paper has the following structure. Section II will discuss about the relation between the size of the network, the required resolution and the simulation method or solver to be used. The following section will explain the various solvers used to simulate power systems. In Section IV, experimental results of achievable performance for these solvers will be demonstrated.

II. Power System Solvers and Applications

Depending on the size of the power system to be studied, various solvers and simulator packages can be used. The solvers we consider are TS, EMT and also high-resolution FPGA simulation. Several factors influences this repartition like the available computing resource with regards to the solvers used. Other criteria that solvers also exists when choosing a simulation package such as the graphical interface or the capacity to distribute computational tasks automatically in multi-core processors in single and multi-processors computers

Figure 1 depicts the recommended simulation solvers versus the type of study undertaken.

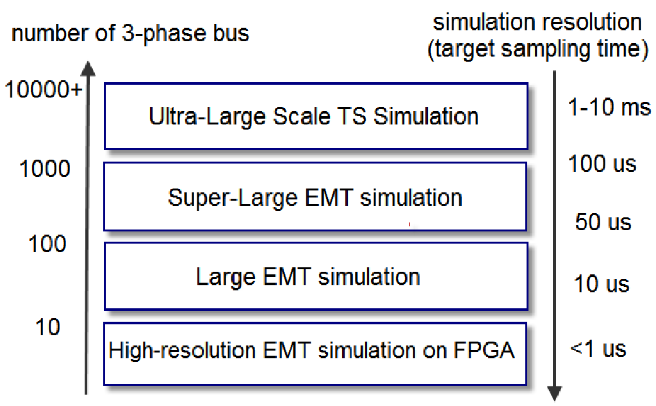


Fig. 1. Target simulation package versus network size

At the center of the chart we find the EMT solvers. This type of simulation is used to study fast phenomenon, such as electrical transients during faults or transmission lines travelling wave propagation effects. It is designed to run at time-step in the range of 10-100µs. Thus, it enables the study of all electric phenomena occurring typically under 2-5 kHz. One of the most well-known EMT programs is called EMTP [10] (along with variant ATP and code updated EMTP-RV) that has been used for many years by utilities around the world.

When real-time EMT simulations are desired for networks with less than 100 buses (three-phase), the eMEGAsim simulator based on ARTEMiS [2] [3] solver package is a good choice because it is directly integrated with SimPowerSystems toolbox (from Matlab/Simulink) and therefore well adapted for this size of network. Integration of eMEGAsim with Simulink also gives the user a great flexibility in terms of modeling and allows easy coupling to other simulation domains through the large number of specialized Simulink toolboxes.

For real-time EMT simulation, with power systems in the range of 100-1000 buses, some improved characteristics are welcome from Hypersim [21]:

1- A specialized graphical user interface with single-line diagram support.
2- Automatic task partitioning for easy multi-processor real-time simulation (up to 128 CPU).

Single-line diagram support simplifies the comprehension and edition of super large EMT diagrams. Hypersim also provides an interface to the Simulink environment through Real-Time Workshop, the code generator of Simulink.

For power systems larger than 1000 buses, , it can become hard to obtain real-time performance using EMT-based solvers. Thus, a real-time TS simulation, such as in ePHASORsim, is preferred. This type of solver typically uses time-step in the order of 1-10 milliseconds and is mainly design to study low-frequency power exchange between the machines, compensator and load, in steady-state or during faults.

At this size of network, network data management can become critical at this point because an erroneous data entry could become very hard to spot. Text-style tabulated data input is preferred in this case. For example, with the Per-Unit scaling and tabulated format of devices like transformers, one can more easily spot an erroneous out-of-range PU entry.

Completely at the other side of the application spectrum, it is often required to model ultra-fast switching devices, like IGBT-based PWM converters using very high-resolution. This can be done using solvers especially coded on FPGAs like eFPGAsim.

A. *Hybrid simulation*

It is also possible to couple these various solvers for differents objectives:

- Hybrid EMT-TS simulation [22] [26]: this type of simulation can be required when a user want to study a part of the network in detail using EMT simulation while considering it interaction with a much larger network simulated using a TS solver.
- Hybrid EMT-FPGA this is actually implemented in eMEGAsim or in specialized motor-HIL simulator[4] where high-frequency converters/motors simulated on FPGAs are coupled with other electric systems running on the CPUs of the simulator.

III. Real-Time Power System Simulation Solvers

A. *Overview*

In this section, we explain the various solvers in more depth. Basically, there are two main type of solution methods for the real-time simulation of power systems: ElectroMagnetic Transient (EMT) simulation and Transients Simulation (TS). They both have many variations. We describe a few of them next.

B. *Nodal solver (EMTP-type)*

In a typical EMT simulation algorithm, each element in the network is replaced by an equivalent circuit consisting of conductances and current sources [8]. The next step for EMT computation is to establish the nodal equations for the substituted network:

$$[G][v(t)] = [i(t)] - [I] \qquad (1)$$

where *[G]* is the nodal conductance matrix, *[v(t)]* is the node voltage vector, *[i(t)]* is the injected current source vector and *[I]* is the known history current vector. The elements of *[G]* and *[I]* in (1) directly depend on the components in the power system (e.g., inductance, capacitance, transmission lines, etc.) and the numerical method (e.g., Trapezoidal rule) chosen for discretization of differential equations which describe the behaviour of the elements. The EMTP and EMTP-RV programs are the archetype of EMT simulation solvers and have been widely used for decades in real-time simulators such as Hypersim and RTDS [25].

1) *EMT solver of Hypersim*

The EMT solver of Hypersim is directly derived from the original EMTP algorithm. It computes its equations by directly discretizing all RLC branches and building the global nodal admittance equation form these. It notably uses the trapezoidal rule of integration and optimal node ordering with regards to switches [10].

2) *EMT solver of RTDS simulator[25]*

The RTDS simulator, from RTDS Technologies, also uses a classic nodal method based on the original EMTP concept. It notably uses the Choleski's method to solve the nodal admittance matrix problem. Choleski's method is a variation of the LU method in which $U=L^T$,and has the obvious advantage of optimizing memory usage.

C. *State-space based solvers.*

This type of solvers is based on the state-space description of the power system being simulated. It's the solver used in SimPowerSystems for Simulink from The Mathworks. However, the SimPowerSystems native solvers are not designed to do real-time simulation. The ARTEMiS solvers used in the eMEGAsim simulator of Opal-RT are designed for that purpose within the Simulink/SimPowerSystems package. They override SimPowerSystems native solvers from within Simulink with 2 types of solvers:

1) State-space solvers with pre-calculation of all matrix sets caused by switches permutations[3]

2) State-Space-Nodal (SSN) solver [2], to be described in the next section

ARTEMiS solvers are designed to take advantage of calculation parallelisation opportunities. The solvers come with Transmission line models that can separate state-space equation into different CPU/cores by using the natural propagation delay of the lines. The SSN solver also allows for direct, delay-free, parallelisation of fully lumped circuits and comes with advanced line models such as Modal Domain [11] and Phase Domain [12]Frequency Dependant line models. The SSN solver also includes interpolation methods for both thyristor valves and forced-commutated converter simulations.

D. *The ARTEMiS-SSN solver*

SSN stands for 'Nodal State-Space' and it means the SSN solver of ARTEMiS is a hybrid solver. The SSN solver of ARTEMiS is a nodal solver, similar to EMTP in many ways, in which the traditional RLC branches equations are replaced by generalized groups described and discretized from their state-space equations.

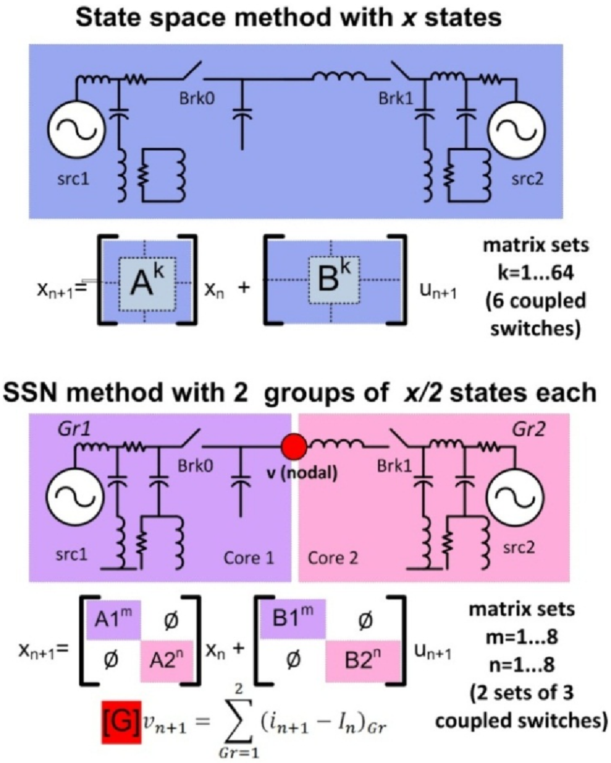


Fig. 2. Virtual group separation in SSN

In state-space solvers, used in SimPowerSystems for example, electric systems are described by state-space equations. The key idea of SSN is to introduce 'nodes' (as in the EMTP nodal method sense) in the system of equations and to use these nodes to introduce a virtual decoupling between the groups of SSN.

These groups can then be described by local state-space systems, including switch permutations which are also decoupled. In the circuit of Fig. 2, imposing a node of a priori unknown voltage creates a virtual separation in the state-space equations. This virtual separation creates a lot of zeros as compared to the global state-space equation, which can increase the speed of calculations. Once each SSN group have been iterated, the common point solution $v_{n+1}(nodal)$ is found using a nodal method with a nodal matrix G and history sources i_{n+1}-I_n computed from all groups.

1) *ARTEMiS L-stable solver*

ARTEMiS uses the state-space (ABCD) equations of the SSN group. It is well-known that the exact solution to the state-space is equal to:

$$x_{n+1} = e^{Ah}x_n + \int_t^{t+h} e^{A(t-\tau)}Bu(\tau)d\tau \qquad (2)$$

where h is the discretisation time step.

The traditional EMTP approach uses the trapezoidal approximation (Padé 1,1) of the matrix exponential, equal to:

$$e^{Ah} \cong \frac{I + hA/2}{I - hA/2} \qquad (3)$$

combined with a linear interpolation of the input during the integration step. The trapezoidal rule is however unstable during fast disturbances, therefore a special method called CDA is applied when a disturbance is detected. During CDA steps of EMTP, the Backward Euler method is used for both matrix exponential and input terms, in addition to a time-step change in the original implementation [11].

Using a higher order in Equation 2 can lead to interesting results especially with regards to stability issues. For example, the ARTEMiS 'Art5' solver, based on the (2,3)-Padé order 5 approximation of the matrix exponential, of formula equal to

$$e^{Ah} \cong \frac{I + 2hA/5 + (hA)^2/20}{I - 3hA/5 + 3(hA)^2/20 - (hA)^3/60} \qquad (4)$$

has a property called L-stability, an extension of A-Stability, which makes it immune to the kind of numerical instability of the trapezoidal rule. It should be noted that the Backward Euler rule is also a L-stable Padé approximations.

2) *Real-time implementation*

L-stable formula

This L-stable discretization formula is more complex to compute that the trapezoidal formula. But it is used only inside the SSN groups where pre-calculation is made and consequently does not affect the real-time performances.

Nodal solution

As in Hypersim, SSN uses a LU method to solve the algebraic nodal admittance problem. Special techniques are used to improve the performance such as optimal ordering techniques[23][24].

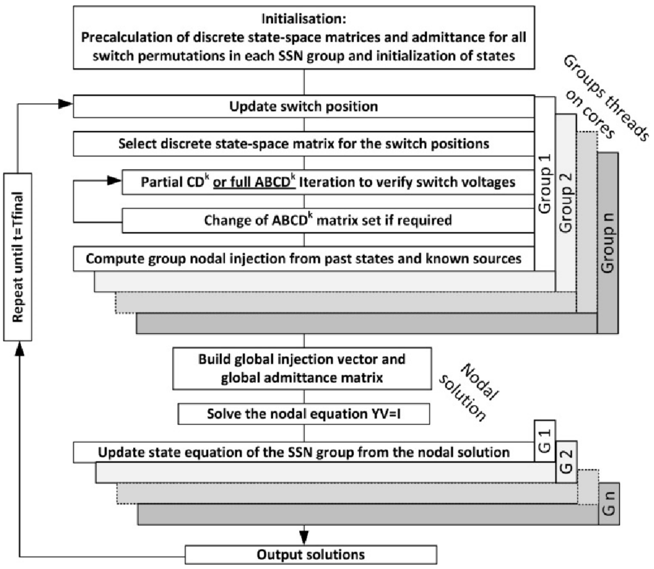


Fig. 3. Parallel SSN algorithm

3) Multi-core parallel SSN solver

One significant advantage of the SSN method is that SSN groups are almost independent of each other and consequently their iterations can be done simultaneously on parallel cores *without any artificial delay in the algorithm*. Fig. 3 shows how the SSN algorithm, is implemented on a parallel computing machine composed of several distinct cores.

E. *Transient Stability Solvers*

From the system theory viewpoint, power systems transient stability (TS) is a strongly nonlinear problem. To assess it accurately, first it should be mathematically described by a set of differential-algebraic equations (DAEs) as follows:

$$\dot{x}(t) = f(x,V) \qquad (5)$$

$$YV = I(x,V) \qquad (6)$$

$$x(t_0) = x_0 \qquad (7)$$

where x is the vector of state variables, V and I are the vector of bus voltages and currents, Y is the nodal admittance matrix of the network, and x_0 is the initial values of state variables.

For transient stability simulation the transmission network is modeled in the main frequency phasor domain, and the dynamics of the system only depend on rotating machines and control devices such as excitation system, power system stabilizer, turbine and governor. Therefore, a simulation time-step in the order of few milliseconds to half of a cycle is sufficient. Equation (5) describes the dynamic behaviour of the system, while equation (6) describes the network constraints on (5).

Numerous TS solvers exists in the literature, we describe here two approaches implemented in the eMEGAsim real-rime simulator of Opal-RT, namely, the Instantaneous Relaxation (IR) method and the Direct Method (DM) solver.

The TS solvers of e*MEGA*sim, e*PHASOR*sim, is designed specifically for real-time transient stability simulation. The tool uses positive-sequence phasor-domain solution of power systems. 3-phase solution is currently being developed as of 2012. The library of the ePHASORsim includes most fundamental components required for power system modeling. The library contains the following models: synchronous generator, load, excitation system, power system stabilizer, turbine and governor, two-winding transformer, and transmission line. This simulation package can be used for dynamic security assessment of large-scale power systems, testing the functionality of hardware such as global control devices for large power grits and micro grids, as well as for training purposes in the academic laboratories or for industry level operators. The tool is linked with MATLAB/Simulink library and is compatible with both Linux and Windows operating systems.

The *ePHASOR*sim involves two types of solvers with different algorithms. The first one is made based on the Instantaneous Relaxation (IR) method that can distribute and run on parallel cores of one or multi-CPUs, and the second one is based on a direct method of the transient stability solution that runs on one CPU core. The detail of each approach is as follows.

1) The IR method based solver[18][19]

In this approach the power grid is torn (i.e. decomposed) into smaller subsystems that are solved individually. At the end of one time-step each subsystem gets updated by external subsystems, and then simulation continues for the next time-step calculations. In each subsystem the differential equations are discretized with the Trapezoidal integration method and the Newton-Raphson iterations are used to linearize and solve the equations.

The IR method can run a real-time simulation of a large-scale system in the range of 7000 buses and 1800 generators on two 12-core e*MEGA*sim targets at a time step of 10 milliseconds.

2) The Direct method based solver

Because of some limitations on the scalability and speed of the IR method, the IR method is currently phase-out in favor of a so-called 'Direct method' (DM). This DM approach uses the explicit Euler integration method to discretize the differential equations. Moreover, sparse matrix solutions have been exploited efficiently to factorize and solve network nodal equations.

ePHASORsim`s direct method can simulate systems in range of 20,000 buses faster than real-time. Consequently, this technique is very well suited for HIL real-time simulation application required to tests global power system control and protection systems implemented in modern SCADA. The research work is underway to simulate even larger systems using parallel computers.

F. *High-resolution FPGA solvers[1][4][5]*

It is often required to simulate power electronic devices with high switching frequencies, well above 10 kHz for example. But it is difficult to obtain a good accuracy of simulation on CPU because the sampling time is too low, often limit above 5µs today because of I/O access time for example. Also, modern controllers can easily have sampling time below 25µs, with fast current loops near 1 µs sampling time. These controllers therefore require that the HIL simulation has a latency in the order of the microsecond, something that can only be achieved today with FPGAs.

On the other hand, implementation difficulties often override algorithmic ones when it comes to implement power system solvers. For example, it is prohibitively expensive in terms of resources to implement a simple divider operator on FPGAs with the consequence that, for example, LU-based solver method cannot be used.
Consequently, FPGAs favor the implementation of simple algorithms like IGBT inverters with PMSM motors, boost converters. The inverters in [4] were implemented using a nodal method with precalculation of the inverses of the nodal matrix, a trick to avoid LU factorisation.

IV. SIMULATION PERFORMANCE

In this section, we describe some example of power system networks simulated with the different solvers described in this paper.

A. *ePHASORsim*

In [14], the simulation of a very large power network with near to 20000 bus and 5000 generators was made in real-time at a time step of 10 milliseconds using the direct method.

TABLE I
Performance of ePHASORsim direct solver on one CPU core

Number of Components				Real-time speed-up factor
Bus	Generator	Controller	Other	
4992	1280	2304	9144	5
7020	1800	3240	12860	3.3
19968	5120	9216	36820	1.25

Table I shows the performance of this solver for three large-scale test cases. The last column of this table lists real-time speed-up factor of each simulation running on e*MEGA*sim simulator powered by a 3.3GHz INTEL CPU. Speed-up factor greater than 1 means that the simulation is faster than real-time.

B. *Hypersim*

In [21], the complete power network of the Province of Quebec, including 25 DFIG-based wind power plants, was simulated in real-time on Hypersim. The network contained the following elements:

- 643 three phase buses
- 34 hydroelectric generators (turbine, AVR, stabilizer)
- 1 steam turbine generator
- 25 Wind Power Plants with DFIG generators
- 7 static VAR compensators
- 6 synchronous condensers
- 167 three-phase lines
- 150 3-phase transformer with saturation modeling

Hypersim used 72 processors of an SGI super-computer to make the real-time simulation of this network at a time-step of 50 µs.

C. *eMEGAsim using ARTEMiS-SSN solver*

In [13], a bipolar HVDC system with multiple switched filter banks was simulated in real-time at a time step below 50 microseconds using the task parallelization feature of the SSN algorithm.

D. *eFPGAsim*

In [4], the real-time simulation of two finite-element-based Permanent Magnet Synchronous Motor is achieved with samples time of 150-500 nanoseconds on a Virtex-6 FPGA interfaced with RT-LAB. The complete circuit also includes a PWM boost converter with a switching frequency up to 50 kHz.

Table II summarize the performance of the various solvers

TABLE II: Performance of different solvers

Solver type	Time step	# of CPU	# of bus	Simulator package
TS (DM)	10 ms	1	20000	ePHASORsim
TS(IR) ** [14]	10 ms	24	8000	eMEGAsim old Phasor tool
EMT	50µs	72	643	Hypersim
EMT	50µs	6	~30	eMEGAsim with ARTEMiS-SSN
EMT on FPGA	500 ns	FPGA	~3	eMEGAsim/ eFPGAsim

** see [14] for more details

V. CONCLUSION

The objective of this paper was to show examples of EMT and TS power system simulation algorithms and achievable performance on different platforms such as multi-core and multi-processor computers for eMEGAsim or high-end SGI multi-processors computers for Hypersim.

The EMT tool of e*MEGA*sim with ARTEMiS-SSN is designed for detailed EMT simulations of large networks such as bipolar HVDC links, wind-farms, FACTS devices and distribution network up to 100 3-phase buses without switch count limit.

For the EMT simulation of super-large network of up to 1000 3-phase buses, Hypersim is well-suited with its higher computing capability on SGI parallel computers along with high quality model editor and automatic task allocation. Automatic task allocation is important in Hypersim, allowing simulation involving more than a 100 processors in parallel.

The ePHASORsim is designed to simulate efficiently systems in the range of 20000 buses and 5000 generators on single core and in real-time using the Direct method approach. Research work is being conducted to increase the size of the system that can be simulated in real-time by using parallel computation with the Phasor tool Direct method. A tearing method similar to the one of SSN is currently being developed at Opal-RT as we are writing these lines to make such a multicore parallel Direct Method Transient Stability program.

VI. REFERENCES

[1] C. Dufour, T. Ould Bachir, L.-A, Grégoire, J. Bélanger, "Real-time Simulation of Power Electronic Systems and Devices" Chapter 15 of the book: "Dynamics and control of switched electronic systems: Advanced perspectives for modeling, simulation and control of power converters" Springer series on Advances in Industrial Control, Francesco Vasca and Luigi Iannelli (Eds.), Springer, 2012. ISBN 978-1-4471-2885-4

[2] C. Dufour, J. Mahseredjian, J. Bélanger, "A Combined State-Space Nodal Method for the Simulation of Power System Transients," *IEEE Trans. on Power Delivery*, vol. 26, no. 2, pp. 928-935, April 2011.

[3] C. Dufour, S. Abourida, J. Bélanger, "InfiniBand-based real-time simulation of HVDC, STATCOM and SVC devices with custom-off-the-shelf PCs and FPGAs," *Proc. of IEEE International Symposium on Industrial Electronics*, pp. 2025-2029, 2006

[4] C. Dufour, S. Cense, T. Yamada, R. Imamura, J. Bélanger, "FPGA Permanent Magnet Synchronous Motor Floating-Point Models with Variable-DQ and Spatial Harmonic Finite-Element Analysis Solvers", 15th Int. Power Electronics and Motion Control Conference, EPE-PEMC 2012, Novi Sad, Serbia, Sept. 4-6, 2012

[5] C. Dufour, J. Bélanger, V. Lapointe, "FPGA-based ultra-low latency HIL fault testing of a permanent magnet motor drive using RT-LAB-XSG", *Simulation: Transactions of the Society for Modeling and Simulation International, SAGE Publications*, Vol. 84, Issue 2/3, pp. 161-172, February/March 2008.

[6] J. W. Bialek, "Why has it happened again? comparison between the UCTE blackout in 2006 and the blackouts of 2003," *IEEE Proc. PowerTech,* pp. 51-56, July 2007.

[7] IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and classification of power system stability," *IEEE Trans. Power System,* vol. 19, no. 2, pp. 1387-1401, May 2004.

[8] R. Diao, V. Vittal, N. Logic, "Design of a real-time security assessment tool for situational awareness enhancement in modern power systems," *IEEE Trans. Power Systems*, vol. 25, no. 2, pp. 957–965, May 2010.

[9] V. Jalili-Marandi, V. Dinavahi, "Instantaneous relaxation-based real-time transient stability simulation," *IEEE Trans. Power Systems*, vol. 24, no. 3, pp. 1327–1336, August 2009.

[10] H. W. Dommel, "Digital computer solution of electromagnetic transients in single- and multiphase networks," IEEE Trans. Power App. Syst., vol. PAS-88, no. 4, pp. 388–399, Apr. 1969.

[11] J. R. Marti, "Accurate Modeling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-101, pp. 147-157, 1982.

[12] A. Morched, B. Gustavsen,, M. Tartibi, "A universal model for accurate calculation of electromagnetic transients on overhead lines and underground cables," *IEEE Trans. on Power Delivery,* vol. 14, No. 3, pp. 1032-1038, July 1999.

[13] C. Dufour, L.-A. Grégoire, J. Bélanger, "Solvers for real-time simulation of bipolar thyristor-based HVDC and 180-cell HVDC modular multilevel converter for system interconnection and distributed energy integration," *CIGRÉ conference proceedings*, Brazil, April 2011.

[14] C. Dufour, V. Jalili-Marandi, J. Bélanger, Laurence Snider, "Power System Simulation Algorithms for Parallel Computer Architectures", Proceedings of the 2012 PES General Meeting San Diego, USA, July 22-26, 2012.

[15] M. La Scala, G. Sblendorio, A. Bose, J. Q. Wu, "Comparison of algorithms for transient stability simulations on shared and distributed memory multiprocessors," *IEEE Trans. Power Syst.*, vol. 11, no. 4, pp. 2045-2050, May 1996.

[16] F. L. Alvarado, "Parallel solution of transient problems by trapezoidal integration," *IEEE Trans. Power Appar. and Syst.*,vol. PAS-98, no. 3, pp. 1080-1090, May/June 1979.

[17] M. La Scala, R. Sbrizzai, F. Torelli, "A pipelined-in-time parallel algorithm for transient stability analysis," *IEEE Trans. Power Syst.*, vol. 6, no. 2, pp. 715-722, May 1991.

[18] M. L. Crow, M. Ilic, "The parallel implementation of the waveform relaxation method for transient stability simulations," *IEEE Trans. Power Syst.*, vol. 5, no. 3, pp. 922-932, August 1990.

[19] V. Jalili-Marandi, V. Dinavahi, "SIMD-based large-scale transient stability simulation on the graphics processing units," *IEEE Trans. Power Systems*, vol. 25, no. 3, pp. 1589–1599, August 2010.

[20] B. Stott, "Power system dynamic response calculations," *Proc. of IEEE,* vol. 67, no. 2, pp. 219-241, July 1979.

[21] R. Gagnon, G. Turmel, C. Larose, J. Brochu, G. Sybille, M. Fecteau. "Large-Scale Real-Time Simulation of Wind Power Plants into Hydro-Québec Power System", Proc. of the 9th International Workshop on Large-scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Plants, Quebec City, Québec, Canada, October 18-19, 2010

[22] S. Abhyankar, A.J.Flueck, "An Implicitly-Coupled Solution Approach for Combined Electromechanical and Electromagnetic Transients Simulation", Proceedings of the 2012 PES General Meeting San Diego, USA, July 22-26, 2012.

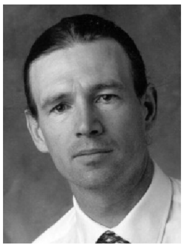
[23] W.F. Tinney, W.S. Meyer, "Solution of large sparse systems by ordered triangular factorization", IEEE Transactions on Automatic Control, Vol. 18 , No. 4 pp. 333 - 346

[24] A. Gomez, L.G. Franquelo, "An Efficient Ordering Algorithm to Improve Sparse Vector Methods," IEEE Transactions on Power System, vol. 3, no. 4, November 1988, pp. 1538-1544.

[25] T. Maguire, "The Implementation of the Cholesky Factorization Routine in the RTDS Real Time Network Solution", Proc. of ICDS '99, Vasteras, Sweden, May 1999

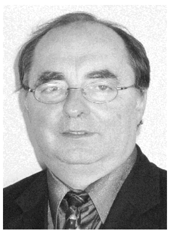
[26] V. Jalili-Marandi, V. Dinavahi, K. Strunz, J. A. Martinez, A. Ramirez, "Interfacing techniques for transient stability and electromagnetic transient programs", IEEE Transactions on Power Delivery, vol. 24, no. 4, October 2009, pp. 2385-2395.

BIOGRAPHIES



Christian Dufour received a Ph.D. degree from Laval University, Quebec, Canada in 2000. He joined Opal-RT Technologies in 1999 where he is the lead researcher in electric system simulation software. Before joining Opal-RT, he worked on the development of Hydro-Quebec's Hypersim real-time simulator, as well as MathWorks' SimPowerSystems blockset. His current research interests are related to algorithmic solutions for the real-time simulation of power systems and motor drives in RT-LAB, the real-time platform of Opal-RT Technologies.

Vahid Jalili-Marandi (S'06-M'11) received his Ph.D. degree in energy systems from the University of Alberta, Edmonton, AB, Canada, in 2010. Currently, he is with OPAL-RT Technology Inc., Montréal, as a simulation specialist in power system applications. His research interests include transient stability simulation methods, large-scale power systems simulation, parallel and real-time simulation, and general purpose computing on GPUs.



Jean Belanger (M'87) is the founder, CEO and CTO of Opal-RT Technologies, a manufacturer of real-time multi-domain simulators. He received the B.S. degree in electrical engineering from Laval University, Quebec City, QC, Canada, in 1971, and the M.S. degree from the École Polytectnique de Montreal, Montreal, QC, Canada. Since 2001, Mr. Bélanger is a fellow of the Canadian Academy of Engineering.