Distributed Real-time Simulation of Power Systems Using Off-the-shelf Software

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Abstract

This paper presents an innovative approach to the problem of rapid simulation of complex power systems. The popular commercial software package, Simulink, when combined with Hydro-Quebec's Power System Blockset (PSB) and Opal-RT's ARTEMIS and RT-LAB provide an off-the-shelf solution for real-time and accelerated non-real-time simulation. Each software product plays a role in the solution. Simulink provides the graphic programming environment, the PSB provides the device library, ARTEMIS corrects for numeric instabilities and imprecision while accelerating the simulation and RT-LAB manages real-time performance and I/O while allowing further acceleration by way of parallel processing.

Sommaire

Cet article propose une nouvelle approche pour la simulation rapide de systèmes électriques complexes. En combinant l'utilisation de Simulink avec le Power System Blockset d'Hydro-Québec, et avec ARTEMIS et RT-LAB d'Opal-RT Technologies, on obtient une solution simple et efficace pour la simulation en temps réel et pour l'accélération de simulations de systèmes électromécaniques. D'une part, Simulink sert d'environnement graphique et le Power System Blockset nous donne une librairie de base. D'autre part, ARTEMIS fournit une méthode d'intégration numerique à pas fixe précise et stable, tout en accélérant la simulation, et RT-LAB coordonne les performances de systèmes distribués qui s'exécutent en parallèle, en temps réel, et des communications entre processeurs.

1.0 Introduction

In control-system test benching, hardware-in-the-loop, rapid control prototyping and other time-critical power-system simulation applications, engineers must use fixed-time-step simulation (as opposed to variable-time-step) to meet hard-real-time constraints. A hard-real-time simulation is one where each simulation step must be completed within a tight deadline, usually measured in microseconds. Even in non-real-time simulation, fixed-time-step simulation may offer a significant speed advantage over variable-time-step simulation. However, choice of a simulation step size is critical to ensure stability of a complex dynamic system.

In the real world, engineers also face real-life constraints: limited budgets and tight deadlines. To do this effectively, they would prefer to use familiar and well debugged software products such as the Mathworks' block-diagram language, Simulink, and its Power System Blockset (PSB) rather than writing their own code. Until recently this has not been possible because these popular tools, although very powerful, were not generally usable for real-time application. To make Simulink and the PSB usable for real-time simulation and to accelerate simulation, Opal-RT Technologies Inc. has developed performance-enhancing software, available commercially as RT-LAB and ARTEMIS.

Power systems constitute a class of stiff systems that are particularly hard to simulate in real-time due to the presence of algebraic and hard nonlinearities such as switching converters and because their eigenvalues vary widely. In order to obtain precise numerical responses, variable-step solvers such as MATLAB's ODE15s (Numerical Differentiation Formula) may be used when long simulation times are tolerable. The built-in fixed-step size integration methods such as Trapezoidal (as used in EMTP) or Tustin (as used in PSB) give faster simulations but are not free from numerical oscillations. The patent-pending ARTEMIS algorithms, based on a suitable order Padé approximation of matrix exponentials, provide L-stable methods [1,2] that are oscillation-free for a wide range of step sizes and are therefore efficient for the fast simulation of power systems [3,4]. This paper illustrates these advantages with reference to a *de facto* standard bench-mark, Kundur's power system.

This power system (Figure 1) is often used as an example in the literature for inter-area oscillation analysis [5], design and test of stabilizers [6] and modeling for simulation purposes [7]. This system is symmetric and each machine is driven by a hydraulic turbine with governor, and an exciter with power system stabilizer [8].

Figure 2 shows this benchmark power system represented as a PSB diagram in Simulink. Area 2 is shown as a mask and the ARTEMIS block is shown in the lower left-hand corner. From a user point of view, ARTEMIS is easy to use: simply place the ARTEMIS block into your diagram and its advanced state-space solver takes over from the built-in solver.

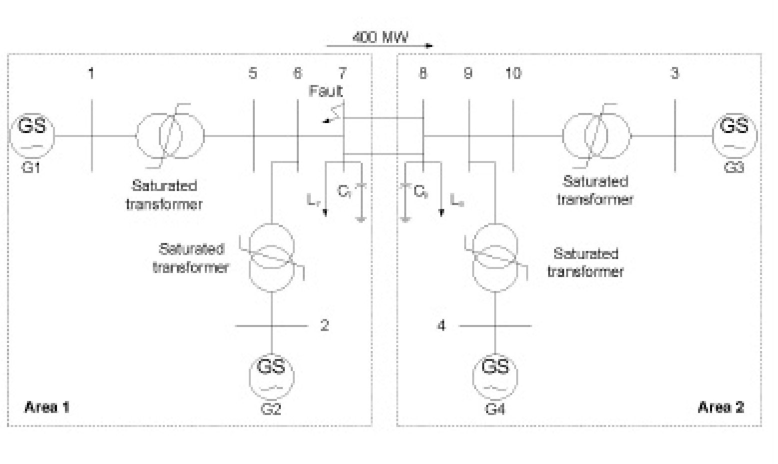

Figure 1: Kundur's Power System.

2.0 Computing Efficiency

A simulation is executed on [0, 2s] with a short-circuit on [0.5s, 0.6s] at the bus 2 between load 7 and the PI line. Table 2 displays the time performance of the simulation versus the integration method and the simulation mode. The first three rows are for Simulink's usual mode of simulation. The last two rows are for compiled simulations under RT-LAB platform with respectively one and two computation nodes. In the last case, the power system is divided into two symmetric areas of equal computational complexity.

The following setup is used:

- **Software:** MATLAB R12, PSB v.2, ARTEMIS v.1.2
- **Hardware:** Pentium II; 550 MHz; 128 MB RAM;
- **Architecture:** one CPU and two CPUs (shared memory).

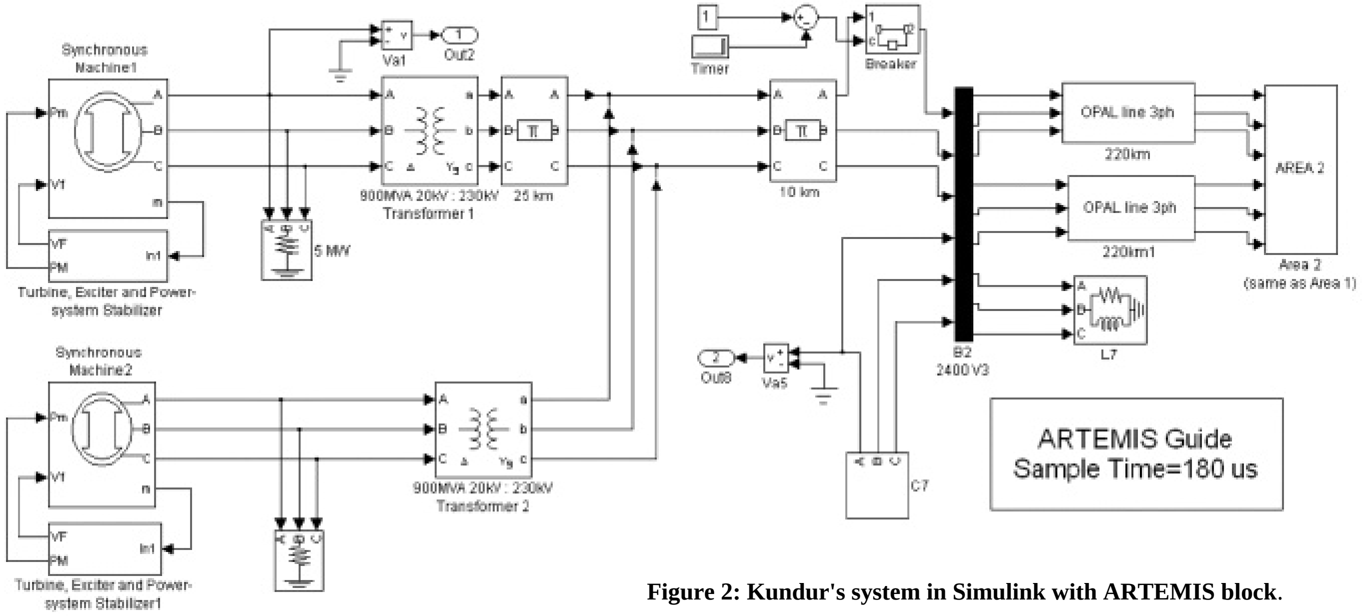

Figure 2: Kundur's system in Simulink with ARTEMIS block.

Table 1: Simulation time with and without ARTEMIS

Simulation mode	Dynamic system solver Ts: stability limit	Execution time per time step (ms)	Total execution time (s) on [0,2s]	Speed-up vs. variable step	Speed-up vs. Tustin
Simulink-mode	Variable step: ode15s (PSBv2)	-	46 min.	1	-
	Tustin (PSBv2.): Ts=130µs	2.2	34	81	1
	ARTEMIS: Art3hd Ts=210µs	1.9	18	153	1.8
Compiled mode under RT-LAB NT Platform	ARTEMIS: Art3hd Ts=210µs 1 CPU	0.15	1.5	1840	22
	ARTEMIS: Art3hd Ts=210µs 2 CPUs	0.1	1	2760	34

As seen in Table 1, ARTEMIS fixed-step-size-integration methods can substantially improve the simulation execution time. Furthermore, since the algorithm is not iterative, each simulation step takes a fixed computation time, which is required to meet the hard real-time constraint.

3.0 Simulation stability

In this section, stability and oscillation damping properties of ARTEMIS methods are shown and compared with Tustin of PSB v.2. Figure 3 shows the terminal voltage of machine 1, the current of the transformer's second winding as well as its magnetizing current are displayed so as to show the efficiency of the proposed solvers.

In Figure 4, system responses of machine 1's terminal voltage and current of transformer's secondary winding are displayed in order to show ARTEMIS improvement in terms of stability and numerical oscillation damping. This signal is more meaningful than line voltage near the fault (bus 7) because of the interaction of the machine and the remaining network. Effects of the modeling method are more obvious at this location. Note that Euler's method (ODE1) of Simulink's solver is used for all

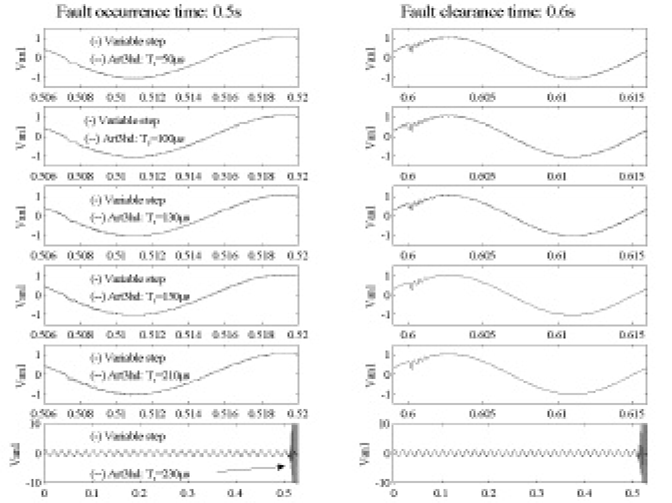

Figure 3: Illustration of Art3hd (ARTEMIS) stability limit.

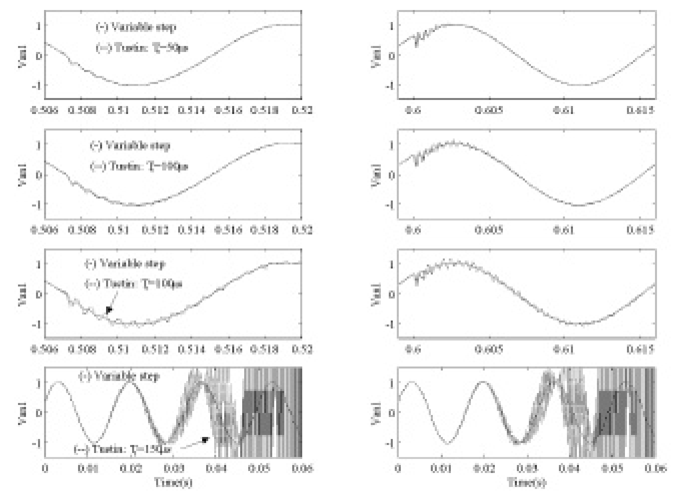

Figure 4: Illustration of Tustin (PSB) stability limit.

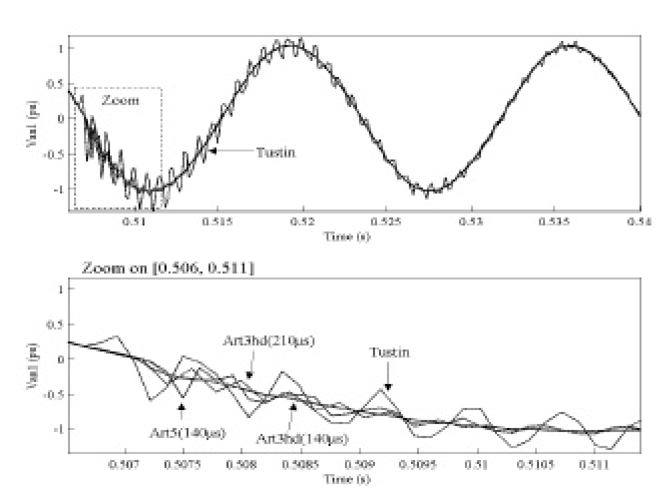

Figure 5: Terminal voltage of machine 1 at fault occurrence time: comparison of integration methods.

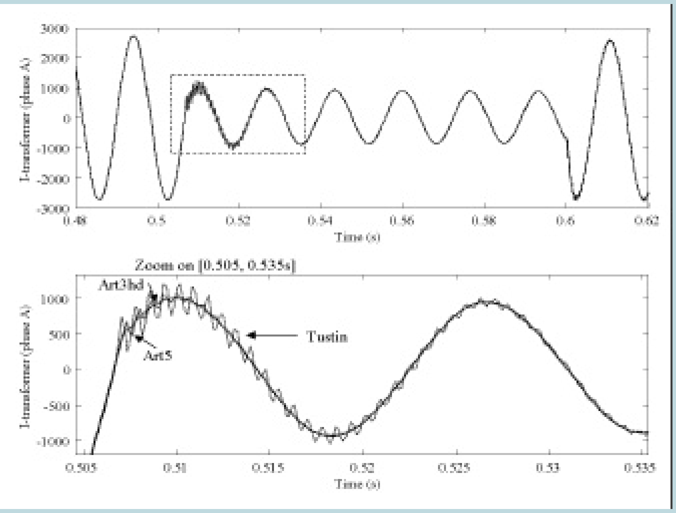

Figure 7: Current at the transformer's secondary winding (machine 1).

fixed-step integration methods under consideration besides ARTEMIS. ODE1 allows solving every continuous systems, i.e. turbines, stabilizers, exciters and machines which, in the last case, are discretized with the forward Euler method only when PSB v.2 is used. In this way, the use of ODE1 avoids compatibility problems such as the machine initialization and is more suited for a comparative study.

It is clear from Figures 3 and 4, that Art3hd of ARTEMIS can simulate the power system with a larger sample time. This constitutes an interesting property for real-time simulation purposes. Though not shown, ARTEMIS'Art5 present intermediary results between Tustin and Art3hd with a loss of stability at Ts=160 microseconds.

Figures 5 and 6 show the terminal voltage of machine 1 at fault occurrence time allowing a comparison of integration methods. Clearly, the ARTEMIS algorithm yields superior numerical results.

In order to evaluate the precision of the different fixed-step size methods, the time-averaged quadratic error of the machine 1's terminal voltage (1pu of amplitude) is calculated on [0 2s] as shown in Equation (1).

$$\varepsilon(t) = \sqrt{\frac{1}{t}\int_0^t \left(x_{fixed-step}(\tau) - x_{variable-step}(\tau)\right)^2 d\tau} \qquad (1)$$

Error in terminal voltage is shown in Figure 8. High values of error due to a small time t are not displayed.

Art5 method exhibits smaller error (Figure 8) than Tustin's. Art3h's error is less important due to its good damping abilities during the transient but tends to be less precise than the other two methods in steady state. Note that an increase of time-sample (Ts = 210µs) or Art3hd close to its stability limit still gives much better results (smaller error increase) than with Tustin (Ts = 140µs) during the transient. The same remark goes with Art5 with a sample-time of 150µs.

Henceforth, the possibility of automatic selection of the fixed-step size integration method is considered in the near future in order to fully exploit the benefits of each integration method of ARTEMIS.

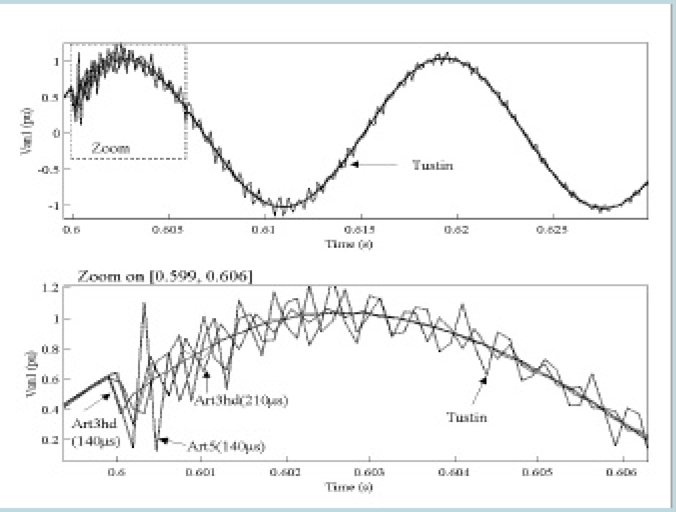

Figure 6: Terminal voltage of machine 1 at fault clearing time: comparison of integration methods.

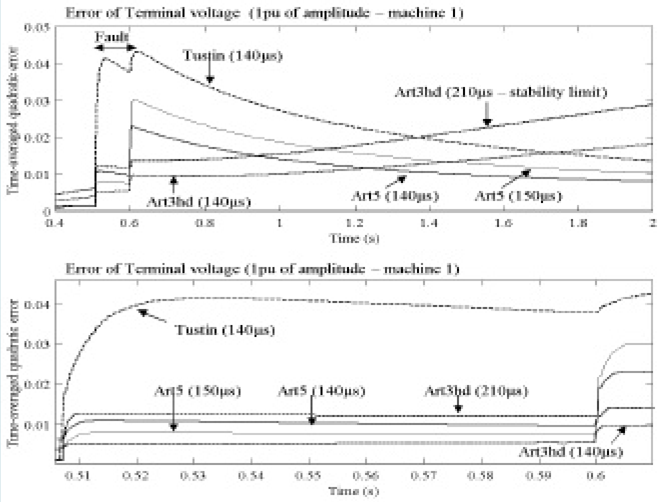

Figure 8: Time-averaged quadratic error of simulation results with Tustin and ARTEMIS versus variable step solver.

For long-term stability Art3hd's response deteriorates versus Tustin's and Art5's, which are quite similar but slightly out of phase with respect to the variable-step integration method. However, a small delay subsists with Art5 as compared to Tustin, which may result in the accumulation of machine modeling error. Continuous models used for ARTEMIS simulation are integrated by a fixed-step size method that may differ from the forward Euler machine model of PSB v2. However, for smaller networks, ARTEMIS results are superior to those obtained with Tustin's method [3]. See [4] for a comparative study of ARTEMIS solver versus Tustin.

The latter consideration combined to the desire to use multi-rate simulation motivate us to develop appropriate voltage-behind-reactance machine model, which is expected to give superior results than those obtained with the whole machine modeled as a current source.

4.0 Conclusion

The off-the-shelf solution for distributed real-time simulation, consisting of Simulink, Power System Blockset, ARTEMIS and RT-LAB, provides better numeric stability, superior damping of oscillations and improved precision compared with those using solely Simulink and the Power System Blockset. The proposed solution is suitable for real-time simulation, hardware-in-the-loop, controller test benches and rapid control prototyping. It can also be used to accelerate simulation for analysis and design of circuits and controllers especially when simulations are run in parallel.

5.0 References

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About the authors

Nicolas Léchevin received the B.Eng. degree from ESAIGELEC in St. Nazaire, France, and his M.Sc. and Ph.D. degrees from the University of Québec, Trois-Rivières, Canada. He is now working for Opal-RT Technologies Inc. as a power-system simulation specialist. His research interests include control, estimation and numerical simulation applied to robotics and electric power systems.

Camille A. Rabbath obtained his Ph.D. degree from McGill University, Montreal, Canada in 1999. Since then he has been an adjunct professor at McGill University and a consultant in control systems for Opal-RT Technologies, Inc. His research interests include digital control of engines, sampled-data control systems analysis and design, distributed simulations, and multi-rate modeling, simulation and control.

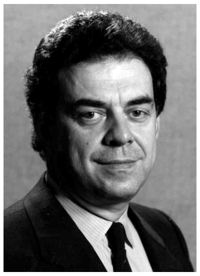
Paul Baracos, Ph.D., has been involved in simulation and control systems since 1976. He has degrees in Physics, Systems Design and Mechanical Engineering and twenty years experience as a professional engineer. He joined Opal-RT as Director of Products in 2000.

Appointment

Anastasios (Tas) Venetsanopoulos named Dean of the Faculty of Applied Science and Engineering at UofT

The Academic Board of the University of Toronto's (UofT) approved the appointment of Anastasios (Tas) Venetsanopoulos to a five-year term as the Faculty's 12th Dean, effective July 1, 2001. Venetsanopoulos succeeded Michael E. Charles, who concluded his eight-year term as Dean on June 30.

Venetsanopoulos received his Diploma in Engineering degree from the National Technical University of Athens, Greece, followed by M.S., M.Phil. and Ph.D. degrees in Electrical Engineering from Yale University. He joined the Department of Electrical and Computer Engineering at UofT in 1968, and has served as Associate Chair: Graduate Studies and Acting Chair of the Department. In July 1999, he became the inaugural Chairholder of the Bell Canada Chair in Multimedia.



A leading researcher in multimedia systems, digital signal/image processing and digital communications, Venetsanopoulos currently holds research grants from the Natural Sciences and Engineering Research Council (NSERC) and the Province of Ontario Research Centre of Excellence on Communications and Information Technology (CITO). He has served as a lecturer in 138 short courses to industry and continuing education programs. He is a contributor to 29 books and has published over 650 papers on digital signal and image processing, and digital communications.

He has served on numerous boards, councils, and technical conference committees of the IEEE. He has also served as President of the Canadian Society for Electrical Engineering and Vice President of the Engineering Institute of Canada (EIC) and is a Fellow of the IEEE and the EIC.