An Open Source Real-Time Power System Simulator with HIL

Lotfi Baghli [(1)], Gaetan Didier [(2)], Sofiane Bendali [(2)] and Jean Leveque [(2)]
[(1)] Faculte des Sciences de l'Ingénieur, Université Aboubekr Belkaid,
13000 Chetouane, Tlemcen, ALGERIA
[(2)] Groupe de Recherche en Electrotechnique et Electronique de Nancy (GREEN-UHP), Université Henri Poincaré, 54506 Vandoeuvre-lès-Nancy Cedex, France.
e-mail : Lotfi.Baghli@green.uhp-nancy.fr

***Abstract*—This paper presents an open source project that yields to the development of a power system simulator on a low cost DSP board running online and includes hardware in the loop (HIL) to interact with actual components.**

Experimental results of the real-time power system simulator being carried out on the digital signal processor (DSP) board of a 3-phase short circuit and with an external variable load are presented and discussed.

***Index Terms*—Power system, Load flow, Transient stability, Hardware In the Loop (HIL), Real Time Simulator (RTS), DSP.**

INTRODUCTION

Nowadays, renewable energy systems introducing wind turbines, solar generators and hydraulic plants are more and more installed.

To study the impact of putting a lot of small electrical production plants, one must analyse the interaction of these systems not only as standalone devices, but also as a part of a power network. The power system, because of its heavily connected grid, can respond quickly to apparatus and faults. These problems propagate rapidly to connected networks, fragelizing the whole system.

Real-time simulators are expensive equipments. They also require power amplifiers to connect to actual devices under test (synchronous compensator, double fed induction generators (DFIG), circuit breaker, superconducting limiters…) [1][2].

Our approach is an academic essay to answer the need of an inexpensive versatile open source real-time simulator that has a built-in capability to interface with experimental equipments.

This open source software will be available on request to the researchers. The code can be adapted to test different equipments that can be interfaced to a dSPACE DS1104 or equivalent DSP boards. The Hardware In the Loop (HIL) concept is very important since the experiments on real power systems is quite impossible. It is necessary to test real equipments such as power system stabilizers, circuit breaker controllers [3] in a closed loop real-time simulator. We encounter more and more application using HIL or FPGA In the Loop [4]. Unlike Lu et al.[5], who choose to run the RTS on an external PC using a Linux based RT system, we run the RT simulator on the same DSP board that interfaces the HIL. The DSP board offer a more flexible system than an analog reprogrammable VLSI [6]. It is also cost effective.

The aim is to develop or adapt the models of the power system elements (synchronous generators, lines, transformers…) to reflect accurately enough the actual ones.

In this paper, we present our approach and the results we obtained with our self developed real-time simulator (RTS) for power system with and without HIL.

We will first discuss the load flow and transient stability simulation and implementation. We then compare a real-time short circuit study with an offline traditional PC simulation using the original code developed by the authors in a previous study [7]. After that, we will present the HIL design that allows the interaction of an external load with power systems being real-time simulated on board.

DESCRIPTION

Single DSP board solutions are powerful enough nowadays to implement such simulators. We choose one of the most often used DSP single board in the academic world named dSPACE DS1104. It is affordable and many labs already have it for motor control purposes. It contains two DSP; a 250 MHz PowerPC with 32 bits floating point computation capabilities and a slave TMS320F240 mainly used for PWM signal generation in order to drive inverters.

dSPACE offers a full software environment to let the user interact (ControlDesk) with the program running on the DSP board but also performs rapid prototyping and interface with software tools. The RTlib and RTI (Real Time library and Real Time Interface) allow connecting the DSP board hardware (ADC, DAC, digital I/O, timers, serial UART, PWM, encoders…) with the program being executed on the DSP. RTlib is a C runtime library and RTI is a layer over RTlib that allows using the hardware with Matlab Simulink blocks. Thanks to an optimized C compiler and to the Real Time Workshop, one can generate the appropriate DSP-targeted executable code.

Recently, a C++ compiler has also been available with Microtech PowerPC C compiler allowing the use of Object Oriented Programming (OOP). The C++ offers also the complex class that is of great interest for load flow and transient stability code implementation.
This board is very suitable for developing versatile HIL systems as we will show thanks to our study.

POWER SYSTEM MODELLING

The studies concerning power systems have to predict how the system will react on a fault or a change in its structure or in its load.
Therefore, we must implement load flow algorithms as well as transient stability computing routines.

The whole study is done in per unit (p.u.) system. Any p.u. quantity is defined as the ratio of the real quantity to its base value expressed as a decimal [8]. This system has the advantage of knowing immediately if we are at nominal or over-loaded conditions without having to refer to the rated power of the device. All variables are expressed as complex quantities (magnitude and phase).

We focus our study on the 5-bus power network presented on Fig. 1. [9]. A bus is a node where different power network components (generators, transformers, lines, loads) are connected. The size of a network is expressed by the number of buses.
There are 3 kinds of buses: the slack bus (also named swing or reference bus), the PV (generator) bus and the PQ (load) bus.
There is only one slack bus in a network; generally it is the strongest node in terms of power production. The voltage is fixed at this bus in magnitude and phase. The generator buses are called PV buses because voltage magnitude and active power are fixed. For the load buses, the active and reactive powers are known (PQ buses).
In our study example, the NORTH bus is the slack one. The SOUTH bus is a PV one. All others are PQ buses. All the network characteristics and a power system software are available online [7].

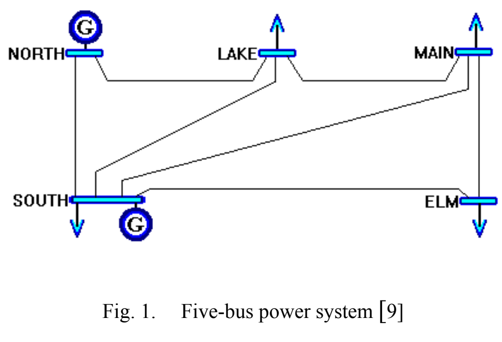

Fig. 1. Five-bus power system [9]

The line model
The power is transported between two buses with lines. We modellize a line by a Π structure [8]. *R* and *X* represent the total serial resistance and reactance. *G* and *B* are the shunt conductance and admittance (Fig. 2.).

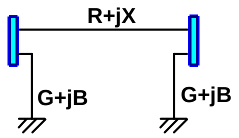

Fig. 2. Model of a mid-length high voltage line

The synchronous generator model
The synchronous generators are represented by an e.m.f. E_g, a transient reactance X'_d and a resistance *R* (Fig. 3.).

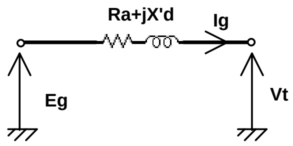

Fig. 3. A Simplified transient model of the synchronous generator

This representation will be used in the transient stability study.
For load flow studies, the rated voltage in magnitude, the active power P_g and the limits of production of reactive power (Q_{gmin}, Q_{gmax}) are the main characteristics of a PV bus.

For the transient model, we need the mechanical equation [8][9]:

$$J\frac{d\omega_m}{dt} = J\frac{d^2\theta_m}{dt^2} = J\frac{d^2\delta_m}{dt^2} = C_m - C_e$$

with:

$$\theta_m = \omega_{sm}t + \delta_m$$

$$\theta = \omega_s t + \delta$$

$$\theta = p\theta_m \text{ and } \delta = p\delta_m$$

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} = P_m - P_e \text{ with } \omega_m \approx \omega_{sm}$$

$$\frac{1}{S_b}\left(\frac{1}{2}J\omega_{sm}^2\right)\frac{2}{\omega_{sm}}\frac{d^2\delta_m}{dt^2} = \frac{P_m - P_e}{S_b} \text{ (W)}$$

We define $H = \frac{1}{S_b}\left(\frac{1}{2}J\omega_{sm}^2\right)$ the ratio of the kinetic energy stored at synchronous speed over the base power in MVA.
We then obtain the mechanical differential equation:

$$\frac{2H}{\omega_{sm}}\frac{d^2\delta_m}{dt^2} = P_m - P_e \text{ (p.u.)}$$

As ω_{sm} and δ_m are mechanical quantities, we obtain:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e \text{ (p.u.)}$$

with $\omega_s = 2\pi f_s$

If we include the mechanical damping, the equation becomes:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e - D\frac{d\delta}{dt} \text{ (p.u.)}$$

So, the state system to be solved is:

$$\begin{cases} \dfrac{d\delta}{dt} = \omega - \omega_s \\ \dfrac{d^2\delta}{dt^2} = \dfrac{\omega_s}{2H}\left(P_m - P_e - D\dfrac{d\delta}{dt}\right) \end{cases}$$

The electrical quantities related to the generator are:

$$E_g = V_t + \frac{I_g}{y_g} \text{ with } y_g = \frac{1}{R_a + jX'_d} \text{ and } I_g = \left(\frac{S_g}{V_t}\right)^*$$

$$P_e = \mathrm{Re}(E_g\, I_g^*)$$

This power equals the mechanical power P_m of the turbine in a steady state operation.

The load model

Loads are represented by their power representation ($P_L + jQ_L$) or by calculating the corresponding admittance in respect to the voltage at the considered bus using:

$$Y_L = \frac{P_L - jQ_L}{V^2}$$

For the transient stability studies the latter is more suitable. It is obtained after a load flow study.

POWER SYSTEM ANALYSIS METHODS

Load flow

In order to compute the power flow and the voltage of all the buses of the network, we have to do a load flow computation. Various methods exist in the literature [9][15]; Gauss-Seidel, Newton-Raphson and the Fast Decoupled Load Flow. These methods have advantages and disadvantages.

The Gauss-Seidel (G-S) method is easy to implant and is suitable for small-sized networks. For bigger networks, the convergence is attainable after a large number of iterations.

The Newton-Raphson (N-R) algorithm converges quadratically, so it takes less iterations than the Gauss-Seidel one. However, it is a more complicated algorithm to implement, it takes a larger amount of memory and it is computation intensive.

For this reason, the Fast Decoupled Load Flow (FDLF) [16] reduces the matrix size by one half, while conserving the quadratic convergence property of N-R. The aim of the FDLF is the strong relation between the active power and the voltage phase and between the reactive power and voltage magnitude.

We used for these studies the G-S one because of the small network size but one can find all the algorithms programmed and given in full source in the Power Designer software that is downloadable from [7].

The load flow algorithm is iterated until the voltage difference, at each bus, between two successive iterations, falls under a fixed tolerance.

The current injected through the i^{th} bus to the network equals:

$$I_i = \sum_{k=1}^{N} I_{ik} = \sum_{k=1}^{N} Y_{ik}V_k = Y_{ii}V_i + \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k$$

Y_{ii} represents the admittance at the node i and Y_{ik} represents the admittance between this node and another one.

The Y matrix is constituted from all these elements. It is built thanks to the power system elements, prior to power flow calculation.

The power at a node is expressed as:

$$S_i = P_i + jQ_i = V_i I_i^*$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{N} Y_{ik}V_k = Y_{ii}V_i + \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k$$

$$V_i = \underbrace{\frac{P_i - jQ_i}{Y_{ii}}}_{KL_i}\frac{1}{V_i^*} - \sum_{\substack{k=1 \\ k\neq i}}^{N} \underbrace{\frac{Y_{ik}}{Y_{ii}}}_{YL_{ik}} V_k$$

To compute V_i^{m+1}, the voltage, at the bus numbered i, at iteration m+1, we use voltages computed at previous iterations V_i^m:

$$V_i^{m+1} = KL_i \frac{1}{V_i^{*m}} - \sum_{\substack{k=1 \\ k\neq i}}^{N} YL_{ik}V_k^m$$

A slightly modified version allows the use of the recently computed voltages at iteration m+1; those below the i th node to evaluate the voltage of bus i:

$$V_i^{m+1} = KL_i \frac{1}{V_i^{*m}} - \sum_{k=1}^{i-1} YL_{ik}V_k^{m+1} - \sum_{k=i+1}^{N} YL_{ik}V_k^m$$

These equations are suitable for PQ buses but for PV buses, the algorithm is adapted, because the voltage magnitude is kept constant to its nominal value and the active power is also fixed, the phase is free to change. The active power produced is fixed to the one of the generator connected to that bus.

Hence, only the phase of the voltage vector at a PV bus changes, but if the reactive power produced by the generator connected to a PV bus reaches its limit, then the PV bus becomes a PQ bus with a fixed power and with a voltage vector free to change in magnitude and phase.

Transient stability

There are two main kinds of transient stability studies:

A. The first-swing stability

In this case, the study is based on a simple model of generators with control systems. We do consider only the first

second following the disturbance. If the network machines remain stable after this second, then the power network is considered as stable for this disturbance.

B. The multi-swing stability

In the latter, the study continues many seconds after the disturbance. It requires more accurate models than the one presented in Fig. 3. It has to take into account control systems (frequency and voltage), in order to reflect a better behavior of the power network machines.

The computation methods used for transient stability studies are step by step time integration of the differential equation of the state system of the generators. We implemented modified Euler, trapezoidal and Runge Kutta 4 integration methods. At each sampling step, we also perform a load flow computation in order to get the new power distribution and bus voltage.
As these algorithms are running online, we must be careful not to overload the floating point PPC of the DSP board. We chose a 1 ms time step for the transient stability study while keeping the inner loop for HIL at 200 µs (vector control, Park transformation, current control,…). The double star PWM has a period of 100 µs, while the outer speed control loop has a sampling period of 1 ms.
The state vector [X_v] of the multi-machine system is equal to:

$$X_v = \left[\delta_0 \quad \delta_1 \quad \cdot \quad \delta_{N_{PV}} \;\vdots\; \omega_0 \quad \omega_1 \quad \cdot \quad \omega_{N_{PV}}\right]^T$$

Each couple of variable ($X_v[i]$, $X_v[N_{PV}+i]$) represents the state variables previously introduced in generator modelling.
At the beginning of the transient stability study (at t=0), the state vector is initialized thanks to a load flow computation with:

$$X_v[i] = \arg\left(E_g[i]\right)$$

$$X_v[N_{PV}+i] = \omega_s$$

(i taking values from 0 to the number of PV buses N_{PV}).
Thus, we include the slack bus, which has a large generator as well.
We also initialize the mechanical power that counter-balances the electrical power at the latter in steady state operation, before the fault occurrence.

STUDIES

We will present two studies done with the real time power system simulator we are developing: a 3-phases short circuit and a sudden external load increase (HIL).

A. The 3-phases short circuit

This study uses no HIL and is intended to verify that the simulation done online on the dSpace DSP board gives the same results as the offline version implemented on a Pentium PC based computer.
It also shows whether the power network can be simulated online given the sampling period without exceeding the DSP computation capability. We tested the reference five-buses power system (Fig. 4.) [9].

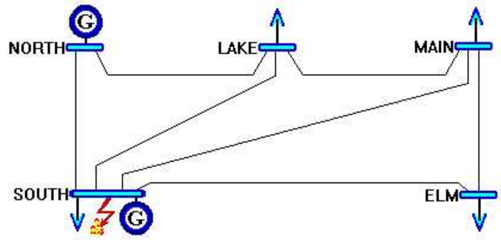

Fig. 4. The five-buses power system. An example of a 3-phases short circuit

The short circuit is a three-phase one happening on the bus SOUTH of the power network. The fault is cleared after 0.1 s. During the fault, the machines at NORTH and SOUTH buses accelerate (Fig. 5.). The internal machine angles evolves consequently (Fig. 6.). The δ_i angle is not the internal machine angle but it is the generator e.m.f. angle in respect to the argument of the voltage of the swing bus at the beginning of the study. The δ_i angle is initialized at the argument of E_{gi}.
We notice that the power generated (Fig. 7.) at the faulty bus drops to zero as well as the voltage magnitude (Fig. 8.) because of the non-impedant fault severity.
The simulation shows that the power network is stable after the first swing because the machine speeds start to oscillate. So, with appropriate damping and speed control, it will return to nominal values. This means that the power network will remain stable with this fault. If we increase the duration of the fault to 0.2 s, we will notice that the system will be no longer stable. It will drop out after the first swing [7] [9].

The ControlDesk capture screen (Fig. 9.) shows the results of the RTS.

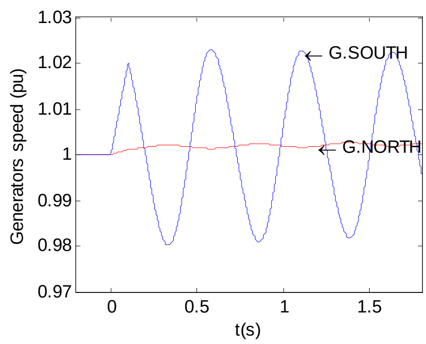

Fig. 5. The 3-phases short circuit transient stability study, the generators speed

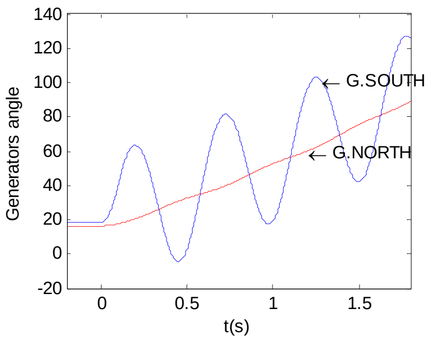

Fig. 6. The 3-phases short circuit transient stability study, the generators angle

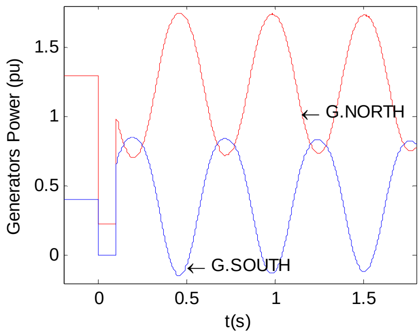

Fig. 7. The 3-phases short circuit transient stability study, the generated power

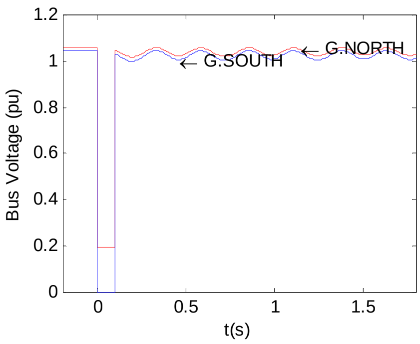

Fig. 8. The 3-phases short circuit transient stability study, the bus voltage

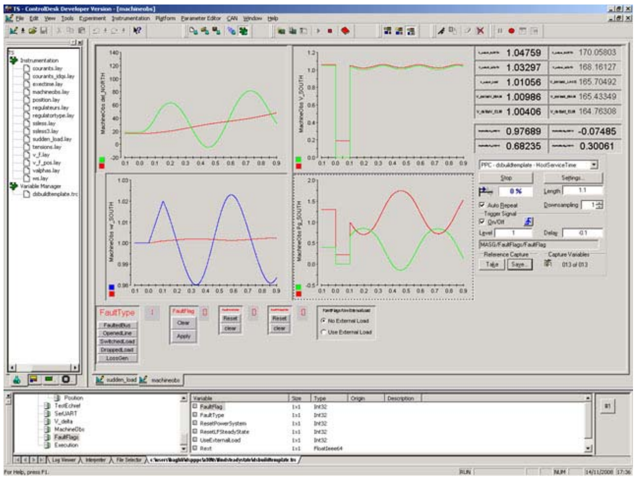

Fig. 9. The real time simulation of a 3-phases short circuit.

B. The sudden external load increase (HIL)

The second study presented in this paper involves the HIL features of the open source software and allows the interface of an external physical component. A rheostatic resistance will be used to represent a variable load on the power network being simulated on the DSP board.

The experimental bench is composed of a 3-phase voltage source inverter driven by a DS1104 dSpace board. The rheostatic resistance load is connected to the inverter in series with a self inductance that will filter the PWM signal to obtain a continuous current in the load (Fig. 10.).

The power system sees the load as an impedance $Z=V/I$.

The bus voltage computed online at each sampling period is applied to the external load, using an inverter. The voltage magnitude is obtained by multiplying the per unit voltage at SOUTH bus by the base voltage V_b. The latter is chosen according to the rheostat impedance and to the maximum current allowed ($V_b = 50$ V, $Z_b = 8\ \Omega$).

For the sake of simplicity, to measure the current and inject it in the power system, we choose DC values with a three phase inverter used in a single phase connection:

$V_{ds}=V_{ref}$, $V_{qs}=0$

$V_{as}=V_{sref}$, $V_{bs}=0$, $V_{cs}=0$ (Clarke transformation)

A computed PWM is used to drive the inverter. Its pattern is centralized around the timer period-match signal that also triggers the ADC SOC (Start Of Conversion) signal of the board. This way of programming the DSP core interruptions allows the minimum current distortion measure because we sample the currents while away from the inverter-legs switching instants.

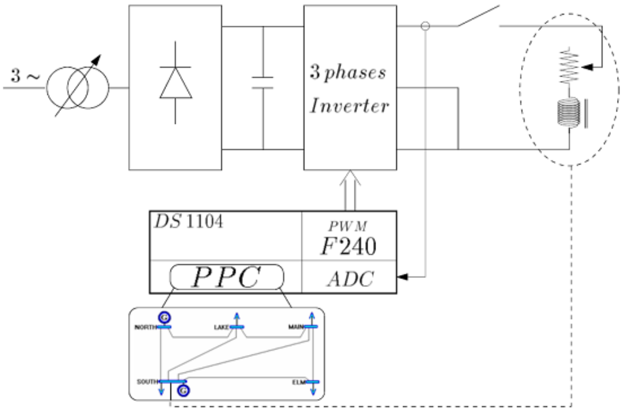

Fig. 10. The experimental test bench for a HIL real-time power system simulator

The 3-phase inverter is connected as on Fig. 10. The fundamental frequency of the inverter is zero; ω_S=0 Hz. The high frequency PWM switching is filtered using an inductance in series with the rheostat.
The current is measured with a Hall sensor and used to compute online the actual value of the resistance. There is no need, as in alternative current, of a sliding window to track the maximum values of the sinusoidal signal to compute the RMS value. For more complex devices to simulate in HIL, this approach has to be used but it will not give special issues because the signal frequency is known.

The experiments consist in a sudden load step of about 0.45 p.u. (Fig. 11. and Fig. 12.). As we can see from the external admittance curve (Fig. 11.), the external load is connected suddenly at t=0 and disconnected manually after about 1.5 s.

During the connection period, the power demand increases. As there is no frequency control, the machine speeds start decreasing (Fig. 14.).

We observe that the two-machine speeds oscillate. The oscillation magnitude depends on the severity of the disturbance (about 45 % load increase at bus SOUTH), the proximity of the bus being overloaded, etc… As there is no frequency or voltage control in the generator model, the speeds do not come back by themselves to 1 p.u. after the disturbance clearance.

Indeed, we already said, that the model used is a "first swing stability" model. Thanks to the open source software, one can enhance the models to suit his need for multi-swing stability studies.

Concerning experiments and sensor offsets, one must launch a load flow study just before the transient one, taking into account, the initial external load, even if it is quite zero because a cumulative error may lead into a simulation deviation.

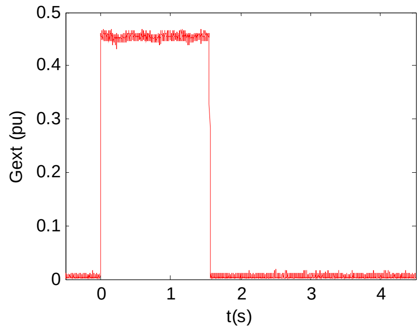

Fig. 11. The sudden external load increase, transient stability study, the external load admittance

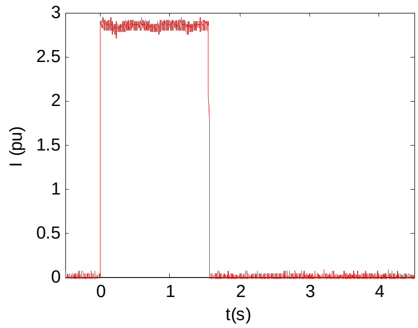

Fig. 12. The sudden external load increase, transient stability study, the actual external current

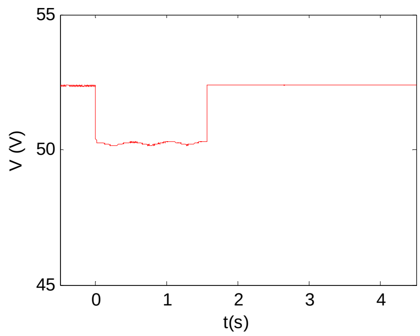

Fig. 13. The sudden external load increase, transient stability study, the actual external load voltage

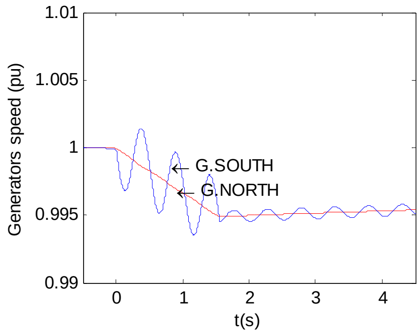

Fig. 14. The sudden external load increase, transient stability study, the generators speed

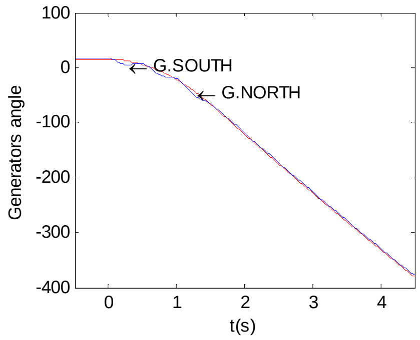

Fig. 15. The sudden external load increase, transient stability study, the generators angle

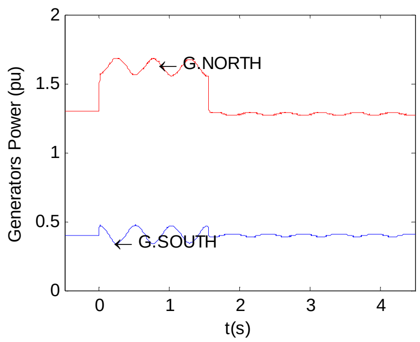

Fig. 16. The sudden external load increase, transient stability study, the generated power

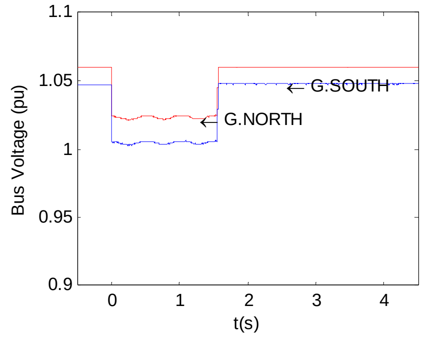

Fig. 17. The sudden external load increase, transient stability study, the bus voltage

This system is a basis for a more complex study we are developing to test superconducting limiters [10] in connected power networks [11]. The prototype of the limiter is under construction. We prefer developing the Real Time Simulator (RTS) because it has two main features: it is cost effective and very versatile since we can implement and refine the system models and computation algorithms. The development took a lot of time but we benefit from previous author experience in power system modeling and simulation.

This open source RTS can be generalized for testing synchronous generators (SG), induction generators (IG), double fed induction generators (DFIG)…

We include in the DSP program, a vector control algorithm that is executed along with the load flow and transient stability routines. A special rewritten F240 slave DSP firmware [12][13] allows the control of two 3-phase inverters with only one DS1104 board because of the Full and Simple PWM module on the TMS 320F240 DSP onboard [14]. This is very suitable for the DFIG or double star induction motor (DSIM).

The authors give the full C/C++ and platform dependent code sources of the developed software [17]. Captures of currents research experiments, including the introduction of Power System Stabilizers (PSS), are also given on [17].

Conclusion

In this paper, we presented our open source software for a real-time power system simulator with hardware-in-the loop. Experimental studies were carried online on the DSP board with the HIL application, allowing the power system to be physically tested with actual components.

In the near future, we will test it with a superconducting limiter we are building. We hope that researchers use this open source simulator for their own power systems HIL studies.

References

[1] L-F. Pak, V. Dinavahi, G. Chang, M.Steurer, P.F. Ribeiro, "Real-Time Digital Time-Varying Harmonic Modeling and Simulation Techniques," *IEEE Transactions on Power Delivery*, Volume 22, Issue 2, April 2007 pp. 1218 - 1227, available online http://dx.doi.org/10.1109/TPWRD.2007.893618

[2] S. Suryanarayanan, W. Ren, M. Steurer, P.F. Ribeiro and G. T. Heydt, "A real-time controller concept demonstration for distributed generation interconnection," *IEEE Power Engineering Society General Meeting,* Montreal 18-22 June 2006, pp3, available online http://dx.doi.org/10.1109/PES.2006.1708926.

[3] R. J. Marttila, E. P. Dick, D. Fischer and C. S. Mulkins, "Closed-loop testing with the real-time digital power system simulator," *Electric Power Systems Research*, Volume 36, Issue 3, March 1996, Pages 181-190, available online http://dx.doi.org/10.1016/0378-7796(95)01030-0.

[4] S. Karimia, P. Poure and S. Saadate, "FPGA-based fully digital fast power switch fault detection and compensation for three-phase shunt active filters," *Electric Power Systems Research*, Volume 78, Issue 11, November 2008, Pages 1933-1940, available online http://dx.doi.org/10.1016/j.epsr.2008.03.023

[5] B. Lu, X. Wu, H. Figueroa, A. Monti, "A Low-Cost Real-Time Hardware-in-the-Loop Testing Approach of Power Electronics Controls," *IEEE Transactions on Industrial Electronics,* April 2007, Volume : 54, Issue 5, pp. 919-931, available online http://dx.doi.org/10.1109/TIE.2007.892253.

[6] George G. Karady and Jun Gu, "Employing reprogrammable analog VLSI in real-time analysis of transient stability," *Electric Power Systems Research*, Volume 77, Issue 8, June 2007, Pages 980-988, available online http://dx.doi.org/10.1016/j.epsr.2006.08.024.

[7] L. Baghli, "Réalisation d'un Environnement Graphique avec Base de Données pour l'Analyse et la Simulation de Réseaux Electriques," *FDP,* pp. 123, June 1994, available online http://www.baghli.com/dl/pfe_baghli.pdf

[8] Stevenson, W.D.Jr., "Elements of Power System Analysis," Mc Graw Hill, 4th edition, 1982.

[9] Stagg, G.W. and El-Abiad, A.h., "Computer Methods in Power System Analysis," Mc Graw Hill, 1968.

[10] C. Schacherer, J. Langston, M. Steurer, M. Noe, "Power Hardware-in-the-Loop Testing of a YBCO Coated Conductor Fault Current Limiting Module," *ASC2008, 1LPG05, pp 5,* Chicago, August 17 - 22, 2008.

[11] J.H. Kim, M. Park, M.H. Ali, A.R. Kim, S.R. Lee, J.Y. Yoon, J. Cho, K.D. Sim, S.H. Kim and I.K. Yu, "A SFCL modeling and application with real HTS material connecting to real time simulator," *Physica C: Superconductivity,* Volume 468, Issues 15-20, 15 September 2008, Pages 2067-2071, available online http://dx.doi.org/10.1016/j.physc.2008.05.128.

[12] K. Marouani, L. Baghli, D. Hadiouche, A. Kheloui, and A. Rezzoug, "Discontinuous SVPWM techniques for double star induction motor drive control," *in Proc. IEEE IECON*, Paris, France, pp. 902-907, Nov. 6-10, 2006, available online http://dx.doi.org/10.1109/IECON.2006.347288.

[13] K. Marouani, L. Baghli, D. Hadiouche, A. Kheloui, and A. Rezzoug, "A New PWM Strategy Based on a 24-Sector Vector Space Decomposition for a Six-Phase VSI-Fed Dual Stator Induction Motor," *IEEE Transactions on Industrial Electronics*, Volume 55, Issue 5, May 2008 pp. 1910 - 1920, available online http://dx.doi.org/10.1109/TIE.2008.918486.

[14] "TMS320F/C240 DSP controllers reference guide, peripheral and specific devices," Texas Instruments, Dallas, TX, Literature Number SPRU161C, 1999, available online http://focus.ti.com/lit/ug/spru161d/spru161d.pdf.

[15] Arrillaga, J. and Arnold, C.P., "Computer Analysis of Power Systems," John Wiley & Sons, 1994.

[16] B. Stott, and O. Alsac, "Fast Decoupled Load Flow," *IEEE Transactions on Power Apparatus and Systems PAS-93*, May 1974, pp. 859-869, available online http://dx.doi.org/10.1109/TPAS.1974.293985.

[17] L. Baghli, "Open Source Real-Time Power System Simulator with HIL," programs for dSPACE boards, available online http://baghli.com/openrts.php.