Abstract-- This paper presents the RT-LAB Electrical Drive Simulator technology along with practical applications. The RT-LAB simulation software enables the parallel simulation of an electrical circuit on clusters of PC running QNX or RT-Linux operating systems at sample time below 10 us. Using standard Simulink models including SimPowerSystems models, RT-LAB build computation and communication tasks necessary to effectively make parallel simulation of electrical systems with low cost off-the-shelf PC technology. To accommodate the high bandwidth of electrical systems, the RT-LAB Electrical Drive Simulator comes with special Simulink-based modeling tools, namely ARTEMIS and RT-Events that permits real-time simulation of electrical systems at practical time step of 10 us but with sub-us equivalent precision through the use of interpolation techniques.

I. INTRODUCTION

Automatic code generation software such as Real-Time Workshop and Autocode has made it possible to build very powerful real-time simulators like RT-LAB without writing any code by hand. An engineer can now go directly from a Simulink or SystemBuild simulation to hardware implementation with minimal debugging time. Since the introduction of real-time simulation, two major applications have emerged: rapid prototyping of controllers and Hardware-in-the-Loop (HIL) testing of production-line controllers. In rapid prototyping, a controller is first modeled in Simulink and the model is then compiled to run on a specified target system allowing testing of the controller algorithm against a real plant. In HIL simulation testing of production-line controllers, the actual controller is tested against a simulated plant model running in the real-time simulator.

While controller rapid-prototyping is a well-established technique, the HIL plant simulation technique is more difficult to realize for electrical systems for several reasons. For example, electrical systems usually have a lot of working modes caused by switches. Electrical systems also tend to be “stiff” by nature, requiring very small time steps or variable-step solvers to achieve convergence and/or accuracy.

The last difficulty comes from the use of power electronic switching devices running at high commutation frequencies. Emulating an IGBT motor inverter requires sub-microsecond precision on the firing time. This is problematic in HIL simulation where current hardware can barely simulate the system at a 10 us time step. For power drive simulation, even such a small time step requires special solvers and interpolation techniques to ensure accurate results.

This paper introduces the RT-LAB Electric Engineering simulator. The paper describes the hardware and software solutions used with some example applications for HIL simulation of electrical systems and drives.

The RT-LAB Electric Engineering simulator has been demonstrated to run real-time applications such as fuel cell hybrid vehicle[2][3][4][5], industrial PMSM drives[7], wind-turbine systems[8][9], off-highway vehicle induction motor drives[10], power system 48-pulse STATCOM simulation[15] and even advanced topologies like matrix converters[11].

II. THE RT-LAB REAL-TIME SIMULATOR

The RT-LAB simulator is designed to make the real-time simulation of Simulink or SystemBuild models on clusters of standard Pentium-based multi-CPU PC.

A. Hardware description

Parallel simulation based on shared-memory multi-CPU PCs is the most commonly used methods for real-time simulation in RT-LAB. With this configuration, one CPU can hold the plant model and I/O interface while the other CPU can hold numerical version of the controllers for example.

Another method involves transmitting data between CPUs on separate PC through external communication links. To achieve this, RT-LAB uses a standard FireWire link or FPGA-based communication link called SignalWire™ capable to deliver up to 1.25 Gbit/s transfer rates, with a latency of 200 ns or recently implemented InfiniBand switching fabric. With SignalWire or InfiniBand links, one can run distributed simulations on PC-cluster at cycle times of less than 10 us without data overruns.

The same FPGA board implements useful functionalities for hardware-in-the-loop testing of electrical systems. The RT-LAB platform is configured to be used with a supplied library of Simulink blocks that allow the user to implement
the DIO, event capture, event generation, and PWM I/O capabilities, all with 10 ns resolution, in the real-time model without coding.

Recently, Opal-RT has introduced the capability to implement models directly in FPGA using the XILINX System Generator tools enabling the generation of FPGA code directly from SIMULINK block diagrams. A power electronic IGBT DC-AC motor drive system has already been implemented with a model update time of 200 nanos. This new technology will however not be discussed in this paper.

B. RT-LAB software toolboxes

The RT-LAB real-time simulator comes with a suite of numerical solvers (ARTEMIS) and power systems models (Time Stamped Bridges). ARTEMIS is an add-on the SimPowerSystems blockset that enables hard real-time simulation. It has also built-in option for interpolation in current-commutated drives (diode, thyristors) [12][13] and comes with specials models for real-time simulation like Decoupling Distributed Parameters Lines to simulate power systems on several CPUs. Time-Stamped Bridges (TSB) [8][14] are interpolation-capable IGBT/MOSFET/GTO models optimized for real-time simulation.

III. CASE 1: PERMANENT MAGNET MOTOR DRIVE WITH AC-SIDE DIODE RECTIFIER

The circuit of Fig. 1 represents a permanent magnet motor drive fed by a 3-phase diode rectifier. The model runs under RT-LAB on a 2.8 GHz dual-Xeon PC at sample times of 10 micros for the motor inverter and 80 micros for the diode rectifier. The diode rectifier uses the ARTEMIS blockset, from Opal-RT, to precompute all modes of the rectifier, thus removing SimPowerSystems mode computation from the real-time loop. A Time Stamped Bridge (TSB), from the RT-Drive blockset from Opal-RT, models the IGBT Bridge is used to accurately compute the voltage-time application time to the motor model. This is important because if the model where to sample the IGBT gate signals at 10 micros without special care, important error would occur in the motor fluxes computation with the PWM carrier set at 9 kHz (~110 us period, ~10 time the simulation time step).

Simulation results of the drive are shown in Fig. 2 and Fig. 3 using an internal Simulink controller. For this case, the speed command is varied in a square wave (10 Hz) fashion between 3000 and 600 rpm. Both figure show the Iq torque control effect that rises when the machine is required to accelerates and goes negative when the machine is commanded to decelerate. One can notice that noise levels are much higher when the interpolation capability of Time Stamped Bridges is disabled. This noise indicates that IGBT switching phenomenon are not well simulated when real-time interpolation is not used.

A real-time simulator running this model has been successfully commissioned by Opal-RT for Mitsubishi Electric Co. of Japan in August 2004[7]. The model is connected to a real external vector controller with a sampling rate of 55 us. The external controller reads the motor currents and the quadrature encoder signals from the simulator and feeds the simulator with the 6 IGBT gate signals. The complete model run in this HIL mode at a sample time of 10 us for the CPU simulating the inverter and 80 us for the CPU running the AC-side of the model.

IV. FUEL CELL HYBRID ELECTRIC VEHICLE DRIVE

The circuit of Fig. 4 represents a fuel cell hybrid electrical vehicle drive system composed of a battery, a fuel cell, a DC-DC converter and PMSM motor drive [2][3][4][5]. The Proton Exchange Membrane (PEM) fuel cell model used in
this study, developed by Emmeskay Inc, is a commercially available control oriented model developed in the MATLAB/Simulink environment. This is a dynamic model and simulates the following thermo-electro-chemical phenomena occurring in the fuel cell: diffusion of gaseous reactants to the reaction sites, electrochemical reactions, combustion product diffusion from reaction sites and heat generation.

In this system, the DC-DC converter controls the power sharing between the battery and the fuel cell. The use of Time Stamped Bridge is mandatory to obtain accurate simulation of the DC-DC converter because its chopping frequency (10 kHz) represent only 1/10 the period of the 10 us model sample time. Errors on IGBT gate sampling can lead to uncontrollability in the real-time simulator. To show this point, the duty-cycle of the DC-DC converter has been scanned and the resulting inductance currents plotted in Fig. 5. The figure shows that the use of Time Stamped Bridges to simulate the DC-DC converter with a 10 us time step (curve b) produces a smooth and accurate response that perfectly matches the reference results obtained with a very low time-step value of 1 us (r). The response has an unacceptable staircase shape when the time stamps are deactivated, even at 1 us (c & g).

The model runs under RT-LAB on a 2.8 GHz dual-Xeon PC at sample times of 10 us. With 6 Time Stamped digital inputs and 5 analog outputs, the sample time rises to 17 micros. The same model can be executed in less than 10 micros with IOs using AMD OPTERON dual-core processors.

V. OTHER RT-LAB DRIVE SIMULATION EXAMPLES

A. Nine-level inverter with 13-winding three-phase transformer

The nine-level inverter with 13-winding three-phase transformer depicted in Fig. 6 is a high-power ultra-low harmonic generating inverter drive. By feeding the DC-stage from winding with different phases, the injected harmonics are minimized at the primary. Nine-level inverter also provides low harmonics at the load. Time Stamped Bridges are used to model the inverter part while a special decoupling transformer models of ARTEMIS permits full mode precomputation of this model and achieve real-time simulation at 75 us time step on a dual Xeon 2.4 GHz computer.

B. Parallel bridge induction motor drive
A critical aspect of the parallel bridge induction motor drive of Fig. 7 is the individual firing delay between parallel IGBT, which can cause huge current spikes in the PMSM drive with AC-side diode rectifier.

C. Matrix converter drive

Recent years have seen renewed interest on matrix converter based drives. Fig. 8 depicts such a drive configuration. It is composed of 18 IGBTs, MCTs or Reverse Blocking IGBTs (RB-IGBTs), grouped in pairs in series-parallel configuration with diodes (except in the case of RB-IGBT). An input filter and voltage clamp circuit complete the circuit. This drive topology has some interesting characteristics of its own. It has intrinsic power regeneration capability. It can have smaller mounting place than conventional AC-AC converters because braking resistor or large electrolytic capacitor are not necessary. It has low total harmonics of input current with high efficiency and power factor. Because the matrix converter drive also has no large DC-bus capacitor (usually electrolytic) so it has longer lifetime and is more reliable.

Opal-RT has recently developed a matrix converter model with interpolation capability designed for real-time simulation of matrix converter drives[11].

CONCLUSION

This paper has presented the RT-LAB simulator and demonstrated its capability to make real-time simulation of motor drives.

The paper has also explained the special simulation tools developed by Opal-RT to enable real-time simulation like RT-Events and ARTEMIS. All the studied case had some high frequency power converter built-in and it has been demonstrated that the use of interpolation technique was mandatory to obtain accurate results.

The RT-Events blockset and especially the Time-Stamped Bridges models were demonstrated to provide for the necessary accuracy to make the real-time simulation of power systems with 2-10 kHz PWM inverters in the 10 to 50 us time step range.

VI. REFERENCES