A Hardware-In-the-Loop Simulation Platform for Prototyping and Testing of Wind Generator Controllers

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SUMMARY

To meet the growing demand for integration of renewable energy sources onto today’s power grids, many engineers from different specialized fields must be involved since various types of studies need to be conducted. The integration of distributed generation (DG) sources significantly changes the characteristics of an entire network. Such interconnection projects will require analysis of power quality, transient response to fault occurrences, protection coordination studies and controller interaction studies.

The first considerable challenge is related to power electronic converters, which are increasing in number and found on most DG sources. Accurately simulating fast switching devices requires the use of very small time steps to solve the system’s equations. Off-line simulation is widely used in the field, but it is time consuming if no precision compromise has been made on models (i.e. the use of average models). Moreover, off-line simulation tools do not offer the wide range of possibilities available with state-of-the-art distributed real-time simulators. Such tools combine, for instance, the efforts of control engineers and specialists from wind turbine manufacturers, who need to test their controllers using hardware-in-the-loop (HIL), together with those of network planning engineers from public utilities, who will conduct interconnection, interaction and protection studies. The eMEGAsim simulation platform is fully integrated with Simulink/SimPowerSystems (SPS) from The MathWorks and EMTP-RV. This makes eMEGAsim a valuable solution for engineers who already have models built with these off-line simulation applications, as well as for less experienced users.

This paper focuses on the prototyping and testing of DG controllers using hardware-in-the-loop simulation. The model described in this paper is a 10-turbine wind farm connected to a single feeder, simulated using an eMEGAsim real-time simulator equipped with 8-processor cores. One of the wind turbines is controlled using an externally emulated controller. The emulated controller model consists of a replica of all other wind turbine controllers, which are locally simulated in the plant model. It is modeled and simulated using a dual-processor core real-time simulator, which interacts with the plant model via analog and fast digital inputs and outputs.

This paper validates the proposed real-time simulator for the study of wind-farm electromagnetic disturbance studies with HIL-connected DFIG controllers, specifically that the simulator can be interfaced with high-frequency PWM controllers without distortions caused by the sampling time of the simulator.

KEYWORDS

DFIM, doubly-fed induction generator, electromagnetic transients, hardware-in-the-loop (HIL), power system simulation, Rapid-Control Prototyping, real-time simulation, wind-farms

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1. MODEL DESCRIPTION

The 500 kV network model used in this paper is represented by an ideal voltage source and equivalent system impedance. A dual line 200 km feeder connects the AC system to a 10-turbine wind farm through a 500 / 25 kV transformer. The high-level, single-wire represented schematic diagram of the three-phase system is shown in Figure 1.

![Figure 1 Schematic diagram of the modeled network and wind farm](image)

The model is distributed on eMEGAsim’s dual Intel® Core™2 Quad processors (8 CPUs). CPU1 controls the calculation of network variables and the input/output communications. The wind farm is separated into 5 computation tasks (CPU2, CPU3, CPU4, CPU5, CPU6) with two detailed wind generator models per CPU. One last computation burden is given to CPU7, which simulates the wind generators’ controllers. The controller of WG10 can be switched from internal to external mode, as it is also implemented in an external eDRIVEsim target. This specific model distribution leaves one CPU available, which can be used for implementation of additional network devices. The wind turbine model and the control scheme used for the case study presented in this article were previously described in detail with corresponding equations in [1].

1.1 The Wind Generator Model

The schematic diagram of the doubly fed induction generator (DFIG) wind turbine model and associated controls is illustrated in Figure 2. Overall, the wind generator model is comprised of three parts: the mechanical part, the electrical part and the controls. The DFIGs are simulated using the asynchronous machine model from the standard SPS/Simulink library. The wound rotor model is simulated in the rotor d-q reference frame. The grid connected transformers and the inductive stator-side filters are also simulated using standard library components. The back-to-back PWM Voltage-source converters (VSC) are simulated with a carrier frequency of 2.78 kHz and using the Time Stamp Bridges from the RTeDrive blockset. Further details are given in [4][5]. The model fixed-step size is 30 µs, which gives a sampling factor of about 12 with respect to the switching frequency.

The mechanical part includes the representation of the turbine blade dynamics, the gearbox and shaft (ideal speed multiplier) which couple the wind turbine and the DFIG’s rotor. The turbine dynamics are expressed by the extractible wind power characteristic. The maximum power point tracking (MPPT) is represented by the \( P-\omega \) operating characteristic of the wind turbine and uses the power measured at the point-of-common-coupling (PCC) in order to determine the turbine speed reference. Its operating characteristic is illustrated in Figure 2.
2. SIMULATOR SETUP AND CONFIGURATION

At its core, eMEGAsim has RT-LAB software [6] and commercial-off-the-shelf (COTS) components including dual Intel® Core™2 Quad processors and Xilinx Virtex II™ FPGA processors. eMEGAsim enables fast and accurate simulation of electromagnetic transient phenomena and therefore greater understanding of the power system under study. The use of the QNX® Neutrino® real-time operating system, widely used in mission-critical applications such as medical instrumentation and air traffic control, greatly optimizes the efficiency and sturdiness of the eMEGAsim simulator. The presented model was built using Simulink/SPS along with specialized Simulink toolboxes provided with eMEGAsim [4][5][7].

Figure 3  Hardware-in-the-loop experimental setup

From a high-level perspective, the experimental setup for the study described in this paper consists of one 8-processor eMEGAsim simulator connected to a dual processor eDRIVEsim simulator via analog and digital I/O. The controller reads the DFIG stator voltages and currents as well as the IGBT converter currents and DC-link voltage on the analog I/Os. The controller also reads the rotor angle by reading resolver signals. The controller sends PWM signals that are read and correctly interpolated in the plant simulator. Both target computers are independent, as would be a real device and its associated controller. A setup overview is illustrated in Figure 3.

Most commercial I/O cards are supported by eMEGAsim, including cards from National Instruments,
Quanser, RTD and Sensoray. However, Opal-RT FPGA cards are recommended for electrical applications which require high switching frequencies. Opal-RT’s OP5110 I/O interface card allows for up to 128 channels of time-stamp digital I/O with a resolution down to 10 nanoseconds. For the application described in this paper, the controller emulator and plant (wind farm) are interfaced with a standard I/O configuration: 16 Analog Inputs, 16 Analog Outputs, 16 Time-Stamp Digital Inputs and 16 Time-Stamp Digital Outputs.

3. EXPERIMENTAL RESULTS

This section describes the results obtained on the experimental simulator set-up. First, a steady-state analysis of analog signals sent from the plant simulator to the external controller was performed. The objective of this test is to show the accuracy obtained when using the real-time compensation of switching events that the RTeDrive blockset offers.

The second test is a three-phase fault on Bus 2 (refer to Figure 1) simulated with the internal (no I/O) and the externally emulated controller. This last test validates the functioning of the externally emulated controller. It is very important to note that the external controller is communicating IGBT gate signals to the plant simulator in the same way that a real controller and DFIG system would. The described HIL set-up does not make use of average models of the PWM converters.

3.1 Compensation of the PWM converter gate sampling with interpolation algorithms

Traditionally, restrictions have existed on the level of precision attainable through the use of digital real-time simulators for simulating high frequency PWM converters. This was due to the simulator’s use of fixed-sampling rates. With eMEGAsim, this issue is addressed by using high-frequency sampling of the IGBTs (or GTO/MOSFET) with FPGA cards together with high-level inverter models that use interpolation techniques to compensate for inter-step events occurring during a simulation. Similar interpolating function blocks are also available to generate the PWM signals in the controller model.

![Figure 4](image)

Figure 4 Steady-state stator currents measured at the analog output of the plant simulator WITH real-time event compensation.

To express the importance of using interpolation capable algorithms in a real-time simulation, the effect of this interpolation is shown in Figures 4 and 5, where the stator currents read by an oscilloscope connected to the corresponding analog outputs are displayed. Figure 4 shows the stator currents with the interpolation algorithm in use, while Figure 5 shows the same signals without the interpolation algorithm. While Figure 4 traces are regular, those in Figure 5 exhibit a low-frequency beat, which is a direct cause of the imprecise sampling of the converter gate pulses. This effect can be observed in much simpler converter models, namely a single-phase thyristor converter [7].

3
3.2 Validation of the real-time plant simulator HIL-connected to the DFIG controller

In this section, fully digital simulation and HIL test cases are compared. A 3-phase fault is applied on Bus 2 (see Figure 1) and the DFIG voltages and currents are monitored. The fault starts at $t = 0.05$ s and is released at $t = 0.15$ s. The phase-A voltages and currents of both studied cases are compared on Figure 6. One observes that the waveforms are in good agreement, even during transients.

A zoomed-in section is shown on Figure 7. The largest observed difference with the voltage comparison is at fault extinction. More important differences are found between the current waveforms. A phase difference is also observed.

The interactions of the controller with the plant in both scenarios are slightly different because of the added communication delay between the plant simulator and the emulator controller and the ambient noise affecting the analog signals. The instant phase angle and magnitude of the fault current is dependent on the instant load demand and generators participation. A slight difference in control signals may cause a current magnitude and phase angle difference at the DFIG. However, since transient stability is obtained in both cases and that steady-state waveforms are matching, one
concludes that the use of an externally emulated controller using HIL is an interesting solution for designing and prototyping wind turbine controllers.

CONCLUSION

In this paper, a real-time simulator technology suitable for the Hardware-In-the-Loop simulation of DFIG and controllers, associated wind-farm and grid was presented. The effectiveness of the technology was demonstrated by comparing fully numerical simulation results with an HIL-connected DFIG controller simulation. It has also been shown that the sampling effect of the digital simulator was correctly compensated for, and that the simulator is suitable to be driven directly by real controller PWM pulses.

BIBLIOGRAPHY


