Hardware-in-the-Loop Testing for Electric Vehicle Drive Applications

Jason J. Poon, Michel A. Kinsy, Nathan A. Pallo, Srinivas Devadas, Ivan L. Celanovic
Massachusetts Institute of Technology
Cambridge, Massachusetts
Email: jsn@mit.edu

***Abstract*—This paper describes the design, implementation, and validation of a hardware-in-the-loop (HIL) test platform for electric vehicle drive applications. We implement a HIL platform by interfacing a variable speed drive controller with a real-time simulation of an electric vehicle drive. A real-time test bench simulation enables drive cycle testing and fault injection capability for the HIL platform. We demonstrate the prototyping capability of the HIL platform with the EPA Urban Dynamometer Driving Schedule (UDDS) on an electric vehicle drive system. Real-time comparisons with a real, small-scale electric vehicle drive validate the fidelity of the real-time simulation under various operating and fault conditions. Test case simulations demonstrate the fidelity and prototyping capability of the hardware-in-the-loop platform when used for electric vehicle drive testing applications. Additionally, real-time simulation and test results demonstrate the ability of the HIL platform to accurately encapsulate electric vehicle dynamics with time constants that span more than five orders of magnitude.**

***Index Terms*—electric vehicles, power system simulation, power system faults, field programmable gate arrays, DC-AC power converters, vehicle dynamics, system testing, variable speed drives**

I. INTRODUCTION

In recent years, hardware-in-the-loop (HIL) testing has shown significant promise to serve as a comprehensive rapid prototyping and automated testing platform for advanced power systems. HIL testing is a technique that replaces a physical model, such as an electric vehicle drivetrain, with a mathematical representation that fully describes the important dynamics of the physical model. Figure 1 shows a functional block diagram of the hardware-in-the-loop concept. A device-under-test, such as an embedded controller or electronic control unit (ECU), interfaces directly with a low-latency real-time computing platform that computes the response of the physical system. A test bench simulation provides the ability to inject test cycles and faults into the real-time simulation, which enables the device-under-test controller to be tested with a wide range of normal and fault operating conditions [1].

Hardware-in-the-loop enables the testing of closed-loop device-under-test controllers under realistic operating conditions without the need to interface with a high-power system. HIL tools enable: (1) accelerated testing and validation; (2) reduced testing time needed in the lab; (3) simulation of all operating points and scenarios that are difficult or impossible to recreate with a real system; (4) fault injection capability; (5) real-time access to all signals that are difficult to measure in a real system [1], [2]. Existing hardware-in-the-loop tools have been used to test and prototype systems with slower dynamics, including power grid dynamics [3], [4] and power system dynamics [5]–[9].

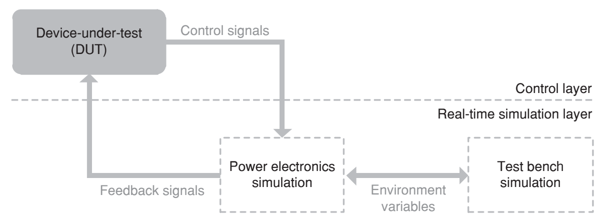

Fig. 1. An overview of the hardware-in-the-loop concept. A device-under-test control layer interfaces with a real-time simulation layer.

However, current state-of-the-art HIL tools have been insufficient for prototyping power electronics converters, which are becoming ubiquitous in energy conversion and power processing devices. A power electronics HIL environment can provide a rapid prototyping platform for the design and testing of power electronics hardware, software, and firmware. Power electronics converters, unlike power systems, are characterized by high-frequency switching devices, including controlled switches (e.g. IGBTs, MOSFETs, thyristors, SCRs) and self-commutating switches (e.g. diodes) that operate on the order of 10 kHz. Furthermore, these switching devices introduce differential and common mode voltages and currents at frequencies on the order of 1 MHz and above. Indeed, a real-time simulation of a power electronics converter with a carrier frequency on the order of 20 kHz requires a sampling time less than 5 μs to capture the important system dynamics [10]. However, the non-linear switching dynamics has posed a challenge for low-latency, real-time simulation of power electronics converters. Existing simulators for power electronics are limited by a sampling time between 10 to 50 μs for real-time execution [11]–[13], or do not have the ability to be executed in real-time [14]–[16].

In [17], [18], we have presented a flexible field programmable gate array (FPGA) environment that solves piecewise linear state-space system models of power electronics converters with a fixed 1 μs simulation time step, including

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input-output latency. Furthermore, in [2], [19], we have presented a real-time simulation for power electronics based on this flexible programmable FPGA environment.

This paper demonstrates a hardware-in-the-loop design and testing platform for electric vehicle drive systems based on the real-time power electronics simulation presented in [2], [17]–[19]. We designed and implemented a real-time simulation of an electric vehicle drive induction machine and a test bench simulation that interfaces with a device-under-test controller. We demonstrate the rapid prototyping capability of the HIL platform with a variety of test cycles and fault conditions. Lastly, we validate the fidelity of the HIL simulation by comparisons with a hardware implementation of an electric vehicle drive.

The paper is organized as follows. Section II provides an overview of the real-time power electronics simulation technology, and describes the modeling and computational approaches used to meet the hard real-time simulation requirement. Section III describes the implementation of the hardware-in-the-loop test platform for electric vehicle drives with a two-level, three-phase voltage source inverter and induction machine. We describe the design and implementation of the device-under-test, real-time power electronics simulation, and test bench simulation. In Section IV, we discuss the qualitative performance of the hardware-in-the-loop platform, and demonstrate its ability to encapsulate electric vehicle drivetrain dynamics with time constants that span more than five orders of magnitude. We present a prototyping demonstration of the hardware-in-the-loop platform using the EPA Urban Dynamometer Driving Schedule (UDDS) for light duty vehicles. Section V presents a fidelity validation of the real-time power electronics simulation. We compare the real-time simulation with a real, small-scale electric vehicle drive setup under various operating and fault conditions. Section VI concludes the paper.

II. Real-Time Power Electronics Simulation

The approach to modeling power electronics converters used in this hardware-in-the-loop platform is based on the work that we have detailed in [2], [18], [19]. We use the generalized automaton modeling approach, which relies on piece-wise linear passive elements, piece-wise linear switches, and current and voltage sources. The switched hybrid system model is given in the state-space form as:

$$\dot{x}(t) = A_q \cdot x(t) + B_q \cdot u(t) \tag{1}$$

where x is the continuous state-space vector, u is the input vector, and A_q and B_q are the continuous state-space matrices for each mode q of the circuit. A mode $q \in \{q_1, ..., q_n\}$ represents a given circuit configuration. The number of total possible circuit configurations n is constrained by $n \leq 2^p$ where p is the number of switches in the circuit.

We discretize the continuous state-space matrices A_q and B_q for each mode using the exact discretization method, given by:

$$\begin{aligned} A_{d(q)} &= e^{A_q h} \\ B_{d(q)} &= \int_0^h e^{A_q t} \cdot B_q \, \mathrm{d}t \end{aligned} \tag{2}$$

where $A_{d(q)}$ and $B_{d(q)}$ are the discretized state-space matrices, and h is the fixed simulation time step. Because the simulation time step is fixed, it follows that the representation for B_d can be formulated as follows:

$$B_{d(q)} = (e^{A_q h} - 1) \cdot A_q^{-1} \cdot B_q \tag{3}$$

Thus, the state-space vector x and output vector y can be computed as:

$$\begin{aligned} x_{k+1} &= A_{d(q)} \cdot x_k + B_{d(q)} \cdot u_k \\ y_k &= C_q \cdot x_k + D_q \cdot u_k \end{aligned} \tag{4}$$

During real-time execution, a direct memory indexing technique controls the selection of the mode q based on inputs u to the system and boundary conditions defined by the output vector y. A linear solver computes the state-space vector and output vector from Equation 4. An internal signal generator and external analog and digital input ports provide the input vector u to the state-space solver. The state-space vector x and the output vector y are accessible in real-time through low-latency analog output ports.

The processor architecture, which is implemented in a field-programmable gate array (FPGA) device, guarantees the duration of execution for each time interval to be shorter than the fixed simulation time step h, resulting in real-time performance regardless of the size of the system. Furthermore, the loop-back latency is minimized with custom designed input-output hardware, and has been characterized to be on the order of 1 μs.

III. Implementation of HIL Electric Vehicle Testing Platform

We demonstrate a complete HIL testing environment for an electric vehicle by interfacing the real-time power electronics simulation presented in Section II with a device-under-test controller and a real-time test bench simulation. As shown in Figure 1, the HIL testing environment is comprised of three functional blocks: (1) the device-under-test controller, (2) the real-time electric vehicle drive model, and (3) the real-time test bench simulation.

A. *Device-under-test controller*

For this demonstration, the device-under-test controller is a scalar volts per hertz (V/F) six-pulse space-vector modulator with closed-loop control of the motor shaft speed. The controller is compiled and executed on a dSpace RT1104 real-time device. The modulator uses a 16 kHz switching frequency with 200 ns deadtime. Real-time controls, including the closed-loop speed control, are computed at a fixed 100 μs time step.

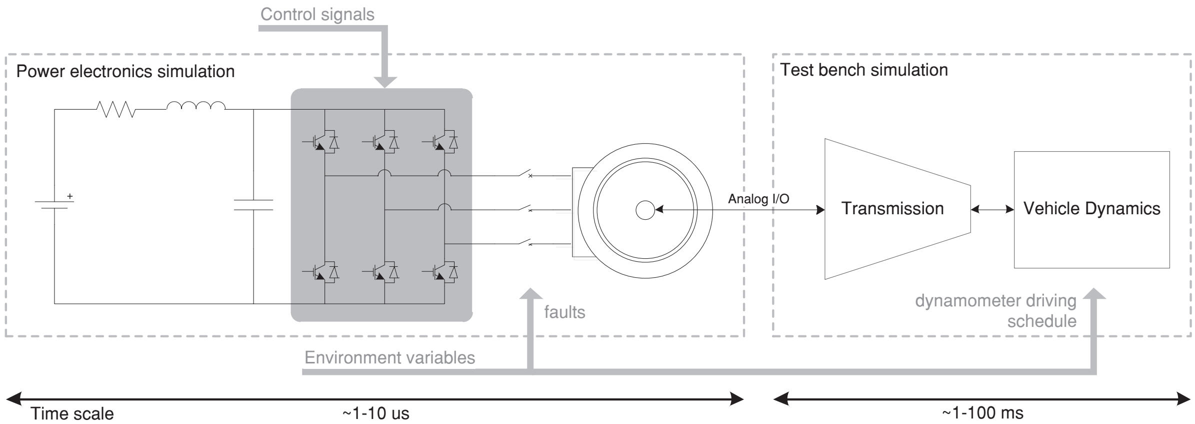


Fig. 2. A functional implementation of the power electronics simulation and the test bench simulation that comprise the hardware-in-the-loop platform. The circuit model of the electric vehicle drive power stage is shown.

The goal of this implementation is to show that the device-under-test controller can be designed, prototyped, and tested without the need to interface with a high-power system. In addition, we will demonstrate in Section V that this controller can be connected to a high-power two-level inverter, and the response of the power system will be identical to that of the real-time simulation.

B. Real-time electric vehicle drive model

The real-time simulation of the electric vehicle drivetrain is based on the modeling and computational approaches described in Section II.

We model the electric vehicle drive power stage as a two-level, three-phase voltage source inverter connected to a squirrel cage induction machine, as shown in Figure 2. A DC source replicates the high-voltage DC bus in the electric vehicle system. The inverter is modeled using six IGBTs with antiparallel diodes. Three single-pole, single-throw (SPST) contactors are placed between each phase of the inverter and induction machine to enable fault injection. The induction machine is modeled using the state-space approach. The per phase equivalent circuit parameters for this induction machine model are given in Table I. This model is based on the Marathon Electric 56H17T2011A, which is used in Section V to validate the real-time simulation.

TABLE I
PER PHASE INDUCTION MACHINE EQUIVALENT CIRCUIT PARAMETERS.

Number of poles	4
Stator resistance (R_s)	9.25 Ω
Rotor resistance (R_r)	7.15 Ω
Stator leakage reactance (X_s)	9.08 Ω
Rotor leakage reactance (X_r)	4.28 Ω
Mutual reactance (X_m)	170 Ω

C. Test bench simulation

The real-time test bench is simulated on the dSpace RT1104 real-time device. During real-time execution, the test bench simulates the vehicle dynamics and generates environment variables for the real-time simulation, including mechanical torque loads on the induction machine shaft and open-phase faults between the inverter and machine, as shown in Figure 2. The test bench enables comprehensive control of the real-time simulation environment, providing the capability to test a wide range of operating and fault conditions.

In this demonstration, the test bench performs a dynamometer driving schedule test on the electric vehicle hardware-in-the-loop platform. The test bench uses the standard EPA Urban Dynamometer Driving Schedule (UDDS) for light duty vehicles. The UDDS is a United States Environmental Protection Agency (EPA) mandated dynamometer test on vehicle emissions and fuel economy for light duty vehicle testing. Specifically, the UDDS emulates driving conditions in urban areas, including city and highway driving. The cycle consists of both motoring and braking conditions. The average load factor of the UDDS is approximately 20 to 25 percent of the motor rated power. The UDDS is used as part of a number of vehicle test procedures, including the U.S. FTP-72 (Federal Test Procedure) cycle, LA-4 cycle, in Sweden as A10 or CVS (Constant Volume Sampler) cycle and in Australia as the ADR 27 (Australian Design Rules) cycle [20]. Although many of these dynamometer drive cycles were originally designed as a benchmark for fossil fuel-based vehicles, these drive cycles can also provide estimates on electric vehicle range and power usage efficiency.

The dynamometer driving schedule test serves as a demonstration of the prototyping capabilities of the hardware-in-the-loop platform. This capability to test over a wide range of operating and fault conditions enables predictions about electric vehicle range and provides the opportunity for controller optimization.

IV. Performance Evaluation

In this section, we discuss the qualitative performance of the hardware-in-the-loop platform, and demonstrate its ability to encapsulate electric vehicle dynamics with time constants that span more than five orders of time magnitude, as shown in Figure 2. Figure 3 shows a demonstration of simulations and tests performed on the hardware-in-the-loop platform. These simulations and tests include:

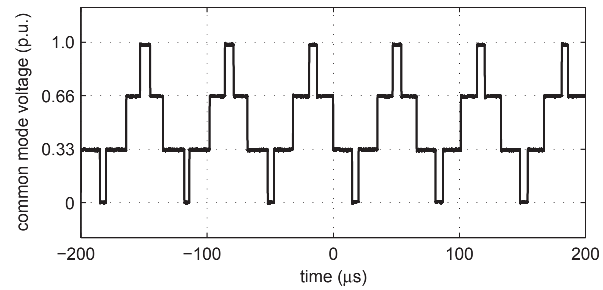
1) induction machine common mode voltage simulation,
2) phase current simulation, and
3) an EPA Urban Dynamometer Driving Schedule (UDDS) test.

Similar to a physical system, these dynamics range from the microsecond scale, as seen in Figure 3a, to the second scale and higher, as seen in Figure 3c.

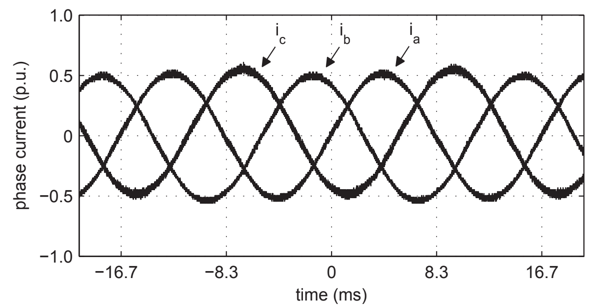
Figure 3a shows a real-time HIL simulation of the common-mode voltage between the neutral point of the induction machine and the negative DC-link. At this microsecond time scale, the real-time simulation, which operates at a fixed 1 μs time step, provides a clear picture of common mode voltages that switch on the order of 1 to 10 μs. This demonstrates the ability of the hardware-in-the-loop platform to capture dynamics and faults that occur at this time scale. This enables optimization of dead time and switching frequency parameters and modulation scheme filtering for applications including common-mode voltage reduction and harmonic reduction.

Figure 3b shows a real-time HIL simulation of the phase currents of a running induction machine. This measurement demonstrates the ability of the hardware-in-the-loop platform to capture dynamics that occur at the millisecond time scale. Section V will validate the fidelity of these dynamics from the real-time simulation. In addition to measurable quantities, the real-time simulation provides estimations about quantities that are difficult to measure, such as rotor flux. These dynamics, including phase currents and motor shaft speed, can be used for high-performance closed-loop control estimators.

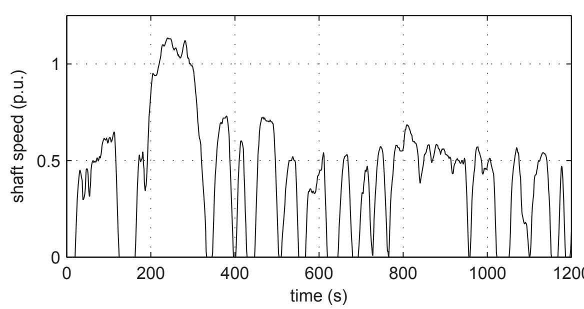
Figure 3c shows a test of the EPA Urban Dynamometer Driving Schedule (UDDS), which is described in Section III-C. We measure the shaft speed of the vehicle drivetrain, while the simulation test bench sets the speed and torque reference points according to the driving schedule. The dynamometer driving schedule test demonstrates the interface between the slower dynamics of the vehicle system, such as the torque response of the drive cycle, and the fast dynamics of the power electronics drive. The hardware-in-the-loop platform encapsulates both slow and fast dynamics, which enables testing for a wide range of operating and fault conditions. The dynamometer driving schedule tests, for instance, provide valuable information about vehicle performance, system efficiency, and battery state-of-charge. Additionally, controllers and data loggers can optimize the long-term performance and reliability of the electric vehicle drive.



(a) Real-time HIL simulation of the common mode voltage from the neutral point of the induction machine to the negative DC-link.



(b) Real-time HIL simulation of phase currents of a running induction machine.



(c) Real-time HIL test of the EPA Urban Dynamometer Driving Schedule (UDDS).

Fig. 3. A demonstration of real-time HIL simulations and tests that are attainable with the HIL platform for electric vehicles. Per unit equivalence is shown in Table II.

The hardware-in-the-loop platform has demonstrated the ability to model a wide range of electric vehicle drivetrain dynamics. This functionality provides the ability to observe faults and fast transients, prototype closed-loop controllers, and optimize long-term performance and reliability.

V. Electric Vehicle Model Validation

The fidelity of the real-time simulation is a critical priority for hardware-in-the-loop applications. In order for the hardware-in-the-loop system to be practical, the response of the real-time simulation must be nearly identical to the response of the physical plant it is simulating. Additionally, the real-time simulation must maintain its fidelity at small time scales with minimal latency.

In this section, we validate the fidelity of the real-time

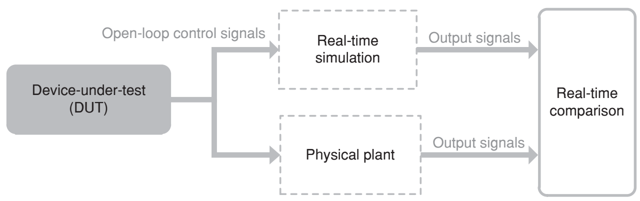


Fig. 4. Functional diagram of the setup used to validate the fidelity of the real-time simulation.

TABLE II
PARAMETERS FOR ELECTRIC VEHICLE DRIVE SYSTEM.

Quantity	Value	p.u.
Number of poles	4	
DC link	230 Vdc	1.0
Motor rated power	0.25 hp	1.0
Full-load (F.L.) speed	1725 rpm	1.0
F.L. torque	1.03 N·m	1.0
Nominal voltage (per phase)	230 Vac	1.0
F.L. current (per phase)	1.0 A	1.0

simulation by running real-time comparisons with a physical plant under three different operating and fault conditions. A functional block diagram of the validation setup is shown in Figure 4. In this setup, the real-time simulator is running a model of the physical plant (e.g. identical topology, parameter values, etc.). A device-under-test sends open-loop control signals to both the real-time simulation and the physical plant in parallel. Various operating and fault conditions are introduced to both the real-time simulation and the physical plant. The output signals from the real-time simulation and the measured values from the physical plant are compared in real-time.

For this validation, the physical plant is a real, small-scale electric vehicle drive system. The electric vehicle drive consists of a 6 kW DC power supply, which is connected to a two-level, three-phase voltage source inverter driving a three-phase induction machine. The induction machine is a Marathon Electric 56H17T2011A model that is described in Section III. We take voltage, current, and speed measurements from this physical plant to serve as a reference for the real-time simulation. Table II presents the parameters for this electric vehicle drive system.

The device-under-test is an open-loop scalar volts per hertz (V/F) inverter controller running on a dSpace RT1104 real-time device. A signal breakout board routes these control signals to both the real-time simulation and the physical plant.

We validate the fidelity of the real-time simulation in three different operating and fault conditions:

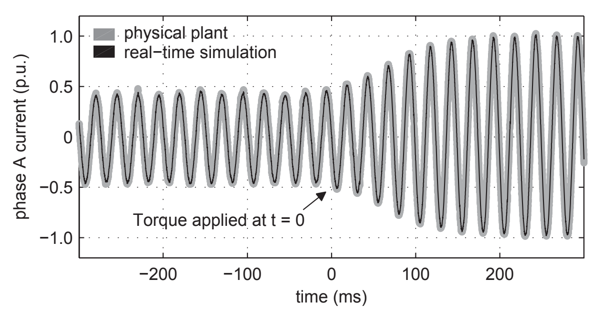
1) a mechanical torque load step on the motor shaft,
2) a gate drive signal loss fault, and
3) an open-phase inverter fault.

The test cases demonstrate the fidelity of the real-time simulation at a variety of time scales, including both slower vehicle dynamics, shown with motor shaft speed comparisons, and faster power electronics dynamics, shown with voltage and current comparisons. The comparisons between the real-time simulation and the physical plant demonstrate that the real-time simulation provides high-fidelity modeling for the hardware-in-the-loop platform.

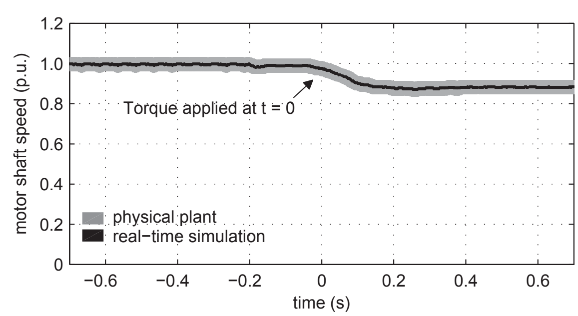
A. Mechanical torque load step

A mechanical torque load step test is used to validate the fidelity of the vehicle dynamics and electric vehicle drive simulation. This test is designed to provide a simple validation of the real-time simulation under dynamic loading conditions, which are common in real-world electric vehicle operation and in dynamometer driving schedule tests. In this test case, the unloaded electric vehicle drive is motored to its full-load speed, and the system is allowed to reach steady state. The test bench simulation synchronizes the 2 N·m torque step signal that is sent in parallel to both the physical plant and the real-time simulation. The test bench simulation sets a reference point for a torque-controlled loading machine that applies the mechanical torque on the shaft of the electric vehicle drivetrain. The test bench simulation sends the same reference point as an analog input signal to the real-time simulation.

Figure 5a shows the phase current of the inverter. Figure 5b shows the rotor shaft speed response of the induction machine. As the figures demonstrate, the response of the real-time simulation is nearly identical to that of the physical plant in both the steady-state and transient regions.

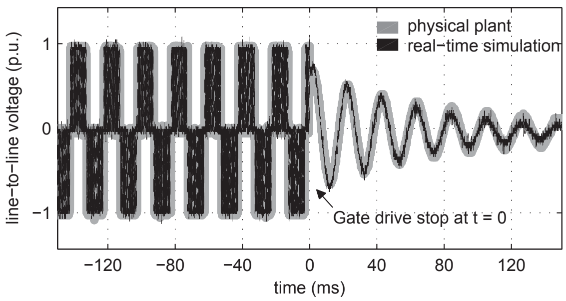


(a) Phase current comparison between physical plant and real-time simulation.

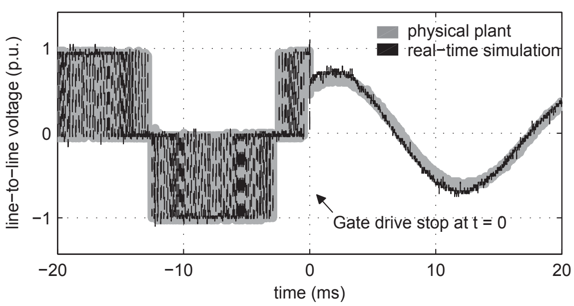


(b) Motor shaft speed comparison between physical plant and real-time simulation.

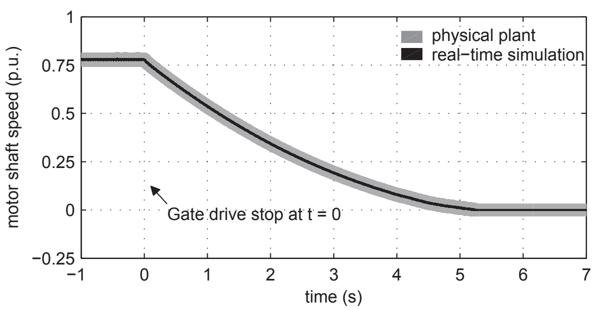
Fig. 5. Validation of mechanical torque load step test case. 2 N·m torque step applied to the motor shaft at $t = 0$.



(a) Line-to-line voltage comparison between physical plant and real-time simulation.



(b) Expanded view of Fig. 6a (line-to-line voltage comparison between physical plant and real-time simulation).



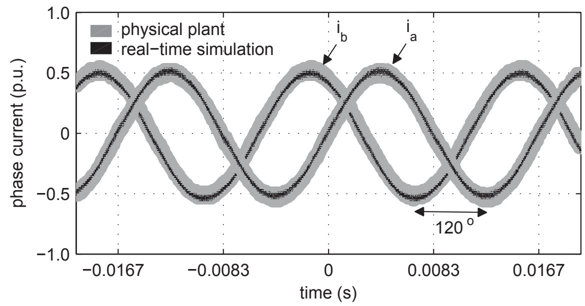
(c) Motor shaft speed comparison between physical plant and real-time simulation.

Fig. 6. Validation of gate drive signal loss fault mode. Gate drive signals are stopped at $t = 0$.

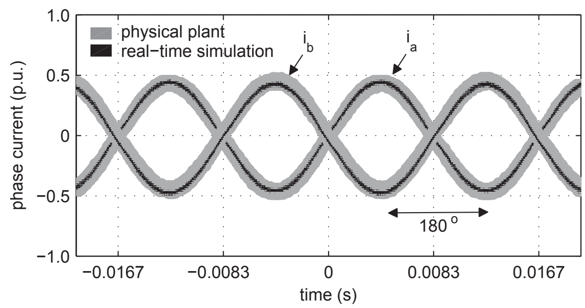
B. Gate drive signal loss

The gate drive signal loss fault mode validates the real-time simulation when the gate drive signals to the running IGBT inverter are abruptly switched to zero. The fault condition emulates a total loss of gate drive signals to the inverter. In this condition, the IGBTs of the inverter do not conduct, but current continues to flow through the anti-parallel diodes across the IGBTs. Additionally, the rotating motor generates a back-EMF as the shaft speed decays. In this test case, the unloaded electric vehicle drive is motored to 75 percent of its full-load speed, and the system is allowed to reach steady state. The gate drive signals are set to zero, and we measure the response of the system.

Figures 6a shows the line-to-line voltage between two phases of the inverter. The comparison shown in Figure 6b demonstrates that the real-time simulation maintains good fidelity during transient conditions at small time scales. Figure 6c shows the rotor shaft speed response of the vehicle drivetrain.



(a) Phase current comparison during normal operation.



(b) Phase current comparison during open-phase fault condition.

Fig. 7. Validation of open-phase fault test case.

C. Open-phase fault

An open-phase fault test case validates the fidelity of the real-time simulation in a fault condition. This test case introduces an open-phase fault between one phase of the inverter and the induction machine. In the physical system, the electrical connection between one phase of the inverter and the induction machine is opened. In the real-time simulation, the open-phase fault is modeled as a single-pole, single-throw (SPST) contactor, as shown in Figure 2. In this test case, the device-under-test controller provides a modulation frequency of 60 Hz. We compare the phase current response of the physical system and the real-time simulation in the normal operating condition. Then, we introduce the open-phase fault to both the physical system and real-time simulation, and we compare the response.

Figure 7a shows the normal operating condition. Figure 7b shows the open-phase fault condition, in which the open-phase fault has been introduced to phase C. The juxtaposition of these normal and fault modes clearly show the amplitude reduction and phase change of the current waveforms caused by the open-phase fault. The figures demonstrate that the real-time simulation closes matches the physical system in both cases. Additionally, this test case validates the modeling of the inverter with zero current flowing through one of the phases.

VI. Conclusions

This paper has demonstrated the design, implementation, and validation of a hardware-in-the-loop (HIL) platform for electric vehicle drive applications. The HIL platform tests the EPA Urban Dynamometer Driving Schedule (UDDS) on an electric vehicle drive real-time simulation. The fidelity of the real-time simulation is validated by means of real-time comparisons with a real, small-scale electric vehicle drive system under three different operating and fault conditions. We demonstrate the fidelity and prototyping capability of the hardware-in-the-loop platform when used for electric vehicle drive testing applications.

References

[1] D. Maclay, "Simulation gets into the loop," *IEE Review*, vol. 43, no. 3, pp. 109–112, 1997.

[2] M. Kinsy, D. Majstorovic, P. Haessig, J. Poon, N. Celanovic, I. Celanovic, and S. Devadas, "High-speed real-time digital emulation for hardware-in-the-loop testing of power electronics: A new paradigm in the field of electronic design automation (EDA) for power electronics systems," in *Power Electronics/Intelligent Motion/Power Quality Conference*, 2011.

[3] D. Westermann and M. Kratz, "A real-time development platform for the next generation of power system control functions," vol. 57, no. 4, pp. 1159–1166, 2010.

[4] C. Dufour, V. Lapointe, J. Belanger, and S. Abourida, "Hardware-in-the-loop closed-loop experiments with an FPGA-based permanent magnet synchronous motor drive system and a rapidly prototyped controller," in *Proc. IEEE Int. Symp. Industrial Electronics ISIE 2008*, pp. 2152–2158, 2008.

[5] S. Abourida and J. Belanger, "Real-time platform for the control, prototyping, and simulation of power electronics and motor drives," in *Proc. 3rd International Conferene on Mondeling, Simulation, and Applied Optimization*, 2009.

[6] C. Bordas, C. Dufour, and O. Rudloff, "A 3-level neutral-clamped inverter model with natural switching mode support for the real-time simulation of variable speed drives," in *Planet-RT Opal White Paper*, 2009.

[7] C. Dufour, G. Dumur, J.-N. Paquin, and J. Belanger, "A PC-based hardware-in-the-loop simulator for the integration testing of modern train and ship propulsion systems," in *Proc. IEEE Power Electronics Specialists Conf. PESC 2008*, pp. 444–449, 2008.

[8] J. Langston, L. Qi, M. Steurer, M. Sloderbeck, Y. Liu, Z. Xi, S. Mundkur, Z. Liang, A. Q. Huang, S. Bhattacharya, W. Litzenberger, L. Anderson, P. Sosrensen, and A. Sundaram, "Testing of a controller for an ETO-based STATCOM through controller hardware-in-the-loop simulation," in *Proc. IEEE Power & Energy Society General Meeting PES '09*, pp. 1–8, 2009.

[9] Y. Liu, Z. Xi, Z. Liang, W. Song, S. Bhattacharya, A. Huang, J. Langston, M. Steurer, W. Litzenberger, L. Anderson, R. Adapa, and A. Sundaram, "Controller hardware-in-the-loop validation for a 10 MVA ETO-based STATCOM for wind farm application," in *Proc. IEEE Energy Conversion Congress and Exposition ECCE 2009*, pp. 1398–1403, 2009.

[10] C. Graf, J. Maas, T. Schulte, and J. Weise-Emden, "Real-time HIL-simulation of power electronics," in *Proc. 34th Annual Conf. of IEEE Industrial Electronics IECON 2008*, pp. 2829–2834, 2008.

[11] J. Wu, C. Dufour, and L. Sun, "Hardware-in-the-loop testing of hybrid vehicle motor drives at Ford Motor Company," in *Proc. IEEE Vehicle Power and Propulsion Conf. (VPPC)*, pp. 1–5, 2010.

[12] M. Harakawa, C. Dufour, S. Nishimura, and T. Nagano, "Real-time simulation of a PMSM drive in faulty modes with validation against an actual drive system," in *Proc. 13th European Conf. Power Electronics and Applications EPE '09*, pp. 1–9, 2009.

[13] A.-L. Allegre, A. Bouscayrol, J.-N. Verhille, P. Delarue, E. Chattot, and S. El-Fassi, "Reduced-scale-power hardware-in-the-loop simulation of an innovative subway," vol. 57, no. 4, pp. 1175–1185, 2010.

[14] J. G. Kassakian, "Simulating power electronic systems—a new approach," vol. 67, no. 10, pp. 1428–1439, 1979.

[15] P. Pejovic and D. Maksimovic, "A method for fast time-domain simulation of networks with switches," vol. 9, no. 4, pp. 449–456, 1994.

[16] J. Alimeling and W. Hammer, "PLECS-piece-wise linear electrical circuit simulation for simulink," in *Proceedings of the IEEE 1999 International Conference on Power Electronics and Drive Systems*, 1999.

[17] D. Majstorovic, Z. Pele, A. Kovacevic, and N. Celanovic, "Computer based emulation of power electronics hardware," in *Proc. First IEEE Eastern European Conf. the Engineering of Computer Based Systems ECBS-EERC '09*, pp. 56–64, 2009.

[18] D. Majstorovic, I. Celanovic, N. Teslic, N. Celanovic, and V. Katic, "Ultra-low latency hardware-in-the-loop platform for rapid validation of power electronics designs," *IEEE Transactions on Industrial Electronics*, no. 99, 2011.

[19] J. Poon, P. Haessig, J. G. Hwang, and I. Celanovic, "High-speed hardware-in-the loop platform for rapid prototyping of power electronics systems," in *Proc. IEEE Conf. Innovative Technologies for an Efficient and Reliable Electricity Supply (CITRES)*, pp. 420–424, 2010.

[20] "The EPA urban dynamometer driving schedule (UDDS)," tech. rep., Environmental Protection Agency (EPA), 2010.