

FPGA-Based PHIL/RCP Simulation of an Electric Vehicle

Danielle S. Nasrallah¹, Michel Lemaire¹, Jean Bélanger¹ and Loïc Boulon²

¹ OPAL-RT Technologies
1751 Richardson, Suite 2525, Montréal, QC, H3K 1G6, Canada
{danielle.nasrallah, michel.lemaire, jean.belanger}@opal-rt.com

² Département de génie électrique et génie informatique
Université de Québec à Trois-Rivières
loic.boulon@uqtr.ca

Abstract

This paper presents the simulation of an electric vehicle featuring: (i) pmsm motor, (ii) power electronics, (iii) batteries, (iv) mechanical drive modeling (taking road profiles into account) and (v) observers and controllers.

The simulation will be achieved in two steps: (i) HIL/RCP where the system is divided into two real-time simulators, the first dedicated for the electric vehicle and the second for the controller and (ii) PHIL where a battery is added to the simulated system.

Realistic aspects are studied, such as: (i) faults and system failures, (ii) performance of the controllers and (iii) numerical stability.

Keywords: PHIL, HIL, RCP, Real-time Simulation, FPGA, Electric Vehicle, Battery, DTC.

1 Introduction

In order to minimize time-to-market of control systems many industries have taken advantage of the computing power of real-time hardware-in-the-loop (HIL) simulators to prototype and test their systems. The increasing demand for faster switching frequency in inverter drives has pushed controller technologies to new heights. FPGAs have become the predominant technology in the real-time simulation market to prototype and test fast-switching inverters, and to simulate power electronics systems and motors at latencies below 500ns. These low time-steps are necessary to properly simulate transient and harmonic effects and to minimize the latency between controller firing pulses and simulator currents fed back to the controller. Additionally, HIL simulations make it possible to test system under hazardous conditions, such as faults, that could otherwise damage costly equipment. It also enables on-the-fly modification of system parameters. Furthermore, Power-HIL (PHIL) simulation offers real power transfer between real and simulated components. This enables tests on parts of the system that can be difficult to properly model or to model in all its complexity.

This paper presents, in a first step, an FPGA-based HIL/RCP simulation of (i) an electric vehicle and (ii) a motor drive, divided between two real-time simulators. The first one includes the power electronics, battery, electric motor and mechanical system models while the second implements the motor controller that is switching at high frequency. In the second step, a PHIL/RCP simulation is covered, where the battery model is replaced by an actual battery cell. The corresponding setup is shown in Fig. 1.

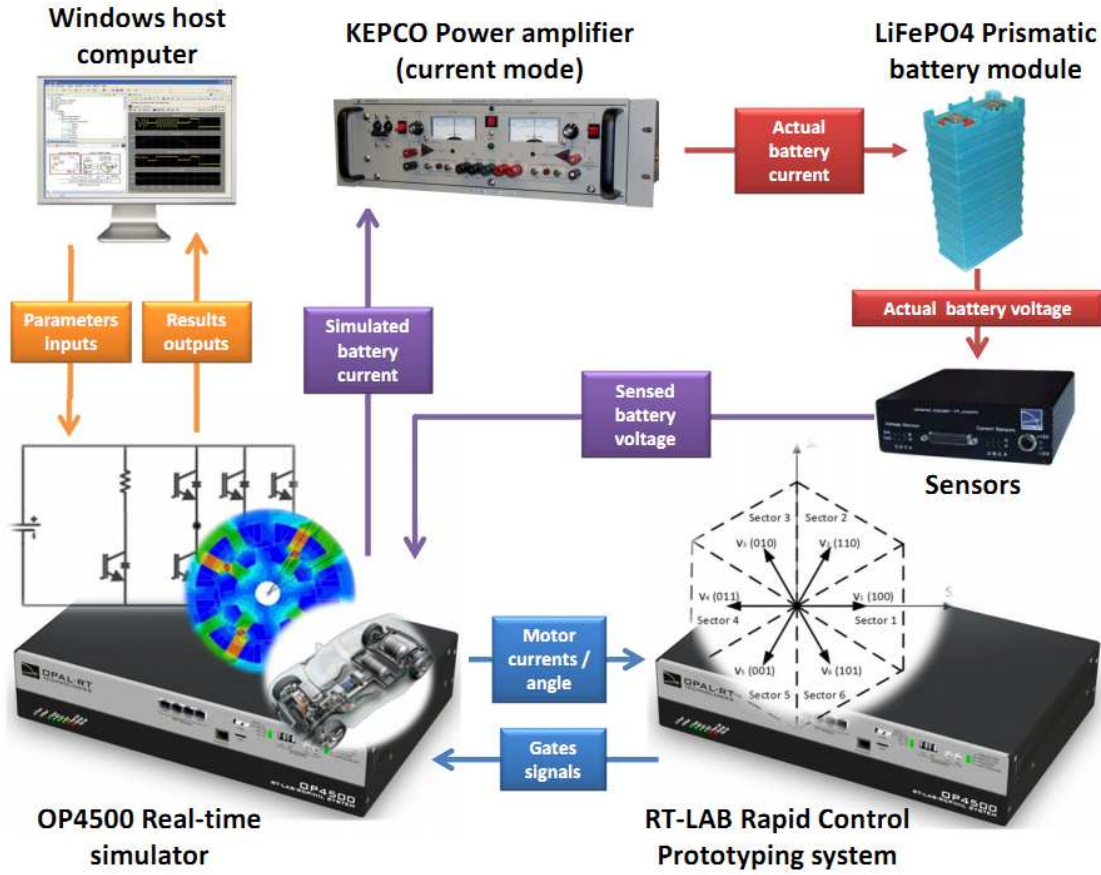


Figure 1: Setup of a PHIL/RCP Simulation of an Electric Vehicle with a Real Battery Cell

2 Modeling

2.1 PMSM

When modeling motors, the accuracy of the model should always be considered hand-in-hand with the test objectives. For instance, when the test targets the linear operating range, where the evaluation of current and torque harmonics is not relevant, a linear dq model is sufficient. Advanced models, that take into account non-linearities such as saturation, are possible using finite element analysis (FEA). Both types are supported by the software used for this experiment.

The PMSM virtual motor model is implemented on the OP4500 Kintex 7 FPGA board and has a total latency of $1\mu s$ from the power electronics gate signal capture at digital input of the real-time simulator to the motor currents at analog outputs of the simulator, thus making it well adapted for PHIL/RCP applications [1,2]. The chosen motor is the internal v-shaped permanent magnet from JMAG. Details on motor parameters are available in Table 1.

The linear dq motor equations are summarized below, namely, the state equation,

$$\begin{bmatrix} \dot{\psi}_d \\ \dot{\psi}_q \end{bmatrix} = \begin{bmatrix} -R_s/L_d & \omega_e \\ -\omega_e & -R_s/L_q \end{bmatrix} \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \begin{bmatrix} 1 & 0 & R_s/L_d \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \\ \psi_m \end{bmatrix}$$

and the output equation,

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 1/L_d & 0 \\ 0 & 1/L_q \end{bmatrix} \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \begin{bmatrix} 0 & 0 & -1/L_d \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \\ \psi_m \end{bmatrix}$$

As for the electromagnetic torque, it is given by:

$$T_{em} = \frac{3}{2}P(\psi_d i_q - \psi_q i_d)$$

Table 1: PMSM Parameters

Maximum power	100 kW
Maximum voltage	500 V
Maximum current	283 A _{peak}
Maximum speed	9000 RPM
Average torque	178 N.m
Inertia moment	$7.24e^{-2}$ kg.m ²
L_d	0.261 mH
L_q	0.555 mH
R_s	1 mΩ
ψ_m	0.1417 Wb
P	4

2.2 Power Electronics

The three-phase two-level power electronic inverter is also simulated on the OP4500 Kintex 7 FPGA board using the *electric-Hardware Solver* eHS from OPAL-RT. The method used in eHS is based on a discrete-time switch model that consists of a constant conductance G_s in parallel with a current source [3]. This method has one drawback, which is the need to select a value for parameter G_s . OPAL-RT developed an algorithm to remedy the problem; optimizing G_s based on the minimization of (i) the commutation losses and (ii) the simulation errors in key-signals between SPS and eHS.

Moreover, the currents computed in the FPGA/PMSM model are injected back into the inverter circuit via controlled current sources, in parallel with RC dampers adequately tuned to ensure numerical stability, as shown in Fig. 2

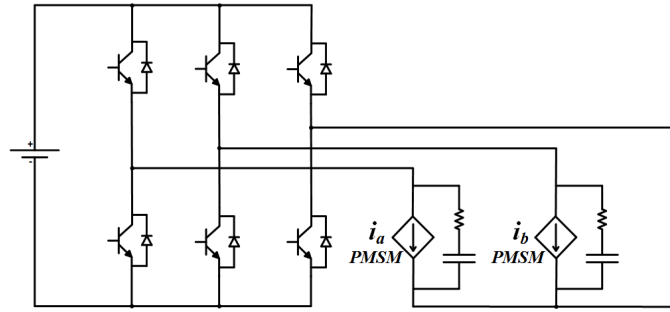


Figure 2: Connection between PMSM and eHS

2.3 Battery

Batteries usually exhibit slow time response. Consequently, complex models can be implemented in real-time on CPU using MATLAB® Simulink®. For this simulation, each battery cell is modeled using the Thevenin equivalent battery model, as shown in Fig. 3 where, R_s is the ohmic resistance, R_c and C represent the battery polarization effect, V_{batt} the battery terminal voltage and V_0 the open circuit voltage [4]. The battery parameters used for this simulation are constant, however, they could be set as a function of the state of charge, and/or the cell temperature, with the implementation of experimental values in a look-up table [5]. The battery pack is modeled as a composition of identical cells having the same parameters and therefore the same terminal voltages. Consequently, a multiplication is applied to the model to simulate the whole battery pack. The equation governing the battery becomes:

$$V_{batt} = V_0 - \left(\frac{R_c}{R_c C s + 1} + R_s \right) I_{batt}$$

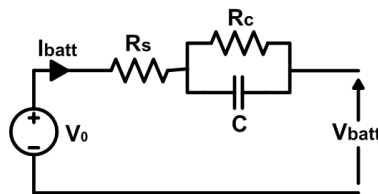


Figure 3: Battery First-Order Model

2.4 Mechanical Power Train

Mechanical systems exhibit slower dynamic response than electrical systems and can be implemented on standard CPU cores. Complex models can be simulated using MATLAB® Simulink®, SimScape™ or other multi-domain simulation. The mechanical system parameters can be changed in real-time, while the simulation is running, to analyze the influence of model parameter changes on the performance of the controller hardware under test [6]. The free-body diagram of the vehicle is pictured in Fig. 4.

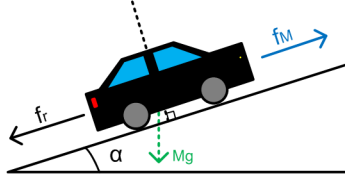


Figure 4: Free-body Diagram of the Vehicle

The mechanical power train is modeled following these steps:

Defining the resistive forces that must be overcome by the electric motor in order to accelerate the vehicle, the free body diagram of the forces acting on a vehicle rolling on a road with a slope α yields:

$$f_r = \frac{1}{2} C_{drag} \rho_{air} A_f v_{vehicle}^2 + M_{vehicle} g \sin \alpha + M_{vehicle} g C_{rr} \cos \alpha$$

Converting the motor torque to its equivalent force leads to:

$$f_M = T_M \frac{k_{gear} k_{diff}}{r_w} \eta_{gear} \eta_{diff}$$

The second Newton law dictates the vehicle speed:

$$v_{vehicle} = \int \frac{F_M - F_{res}}{M_{eq}} dt$$

where the equivalent mass of the car M_{eq} is given by:

$$M_{eq} = M_{vehicle} + \frac{J_w}{r_w^2} + J_m \eta_{gear} \eta_{diff} \frac{k_{gear}^2 k_{diff}^2}{r_w^2}$$

Finally, the motor speed as seen from an encoder is:

$$\omega_m = \frac{k_{gear} k_{diff}}{r_w} v_{vehicle}$$

Table 2: Vehicle Parameters

Road profile slope angle	α (rad)
Vehicle frontal area	A_f (m ²)
Gravity acceleration	g (m/s ²)
Aerodynamic drag coefficient	C_{drag}
Tire rolling resistance coefficient	C_{rr}
Vehicle Mass	$M_{vehicle}$ (kg)
Air density	ρ_{Air} (kg/m ³)
Gear ratio	k_{gear}
Differential ratio	k_{diff}
Gear efficiency	η_{diff}
Differential efficiency	η_{diff}
Wheel radius	r_w (m)
Wheel inertia	J_w (kg.m ²)
Motor inertia	J_m (kg.m ²)
Vehicle speed	$v_{vehicle}$ (m/s)

2.5 Direct Torque Control

The principle of direct torque control (DTC) is to select the appropriate voltage vector according to the stator magnetic flux amplitude and position as well as the error between reference and actual torque. This technique is state-of-the-art; readers are referred to [7] to learn more. Figure 5 shows sectors in stator $\alpha\beta$ plane.

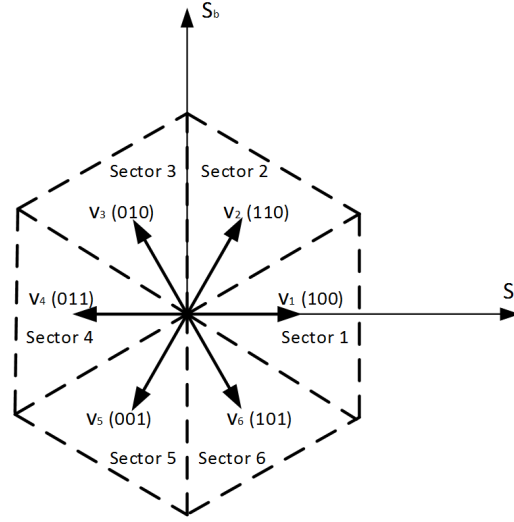


Figure 5: Sectors - Stator $\alpha\beta$ plane

The flux observer computes the stator flux based on (i) the stator current readings and (ii) the stator voltages reconstituted from switches gates. Abundant literature is available on this topic, but for brevity, only two will be cited [7 and 8]. The controller is implemented on the OP4500 Kintex 7 FPGA board using OPAL-RT RT-XSG and Xilinx® System Generator software, see Fig.6. The use of block connection base programming tools greatly simplify the implementation of the controller on FPGA. The maximum switching frequency is set to 100kHz.

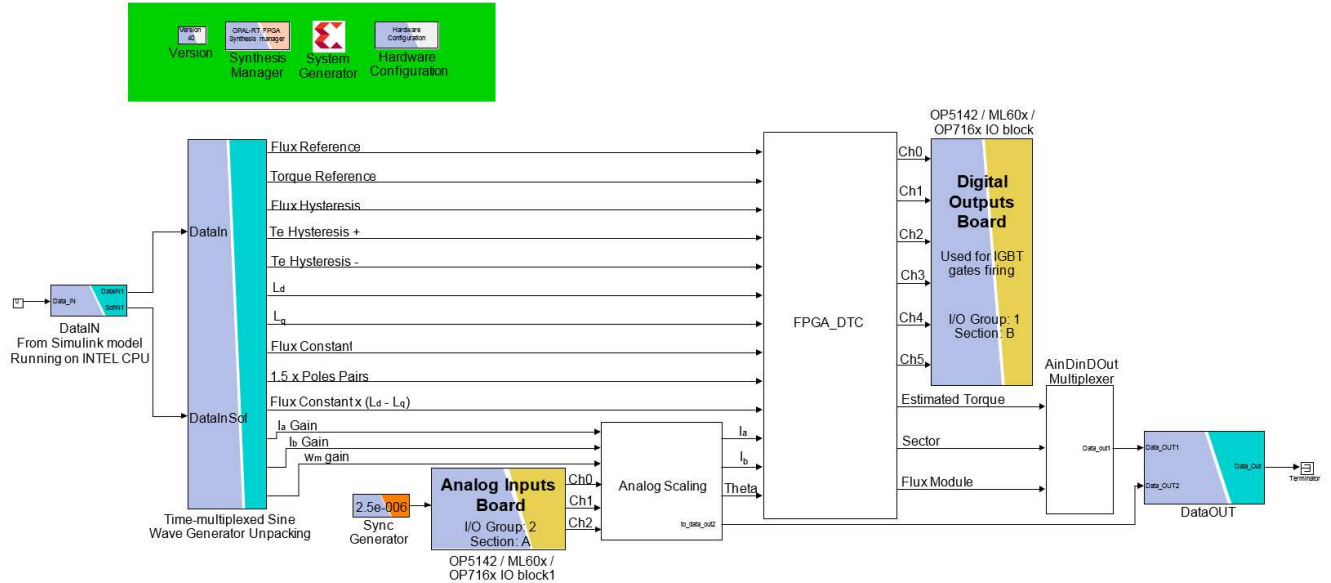


Figure 6: DTC implemented with OPAL-RT XSG and Xilinx® System Generator

3 Real-Time HIL and PHIL Simulation

Simulation will be achieved in two steps:

1. HIL/RCP real-time simulation using RT-LAB software and two OP4500 real-time simulators, where the first target is dedicated to simulating the complete vehicle (including the vehicle dynamic, power inverter, motor and battery) while the second implements the controller.
2. Power-HIL where the battery model is replaced by a real battery operating with an amplifier;

3.1 Hardware in the Loop Simulation

The CPU model to be uploaded on the first target is shown in Fig. 7 below:

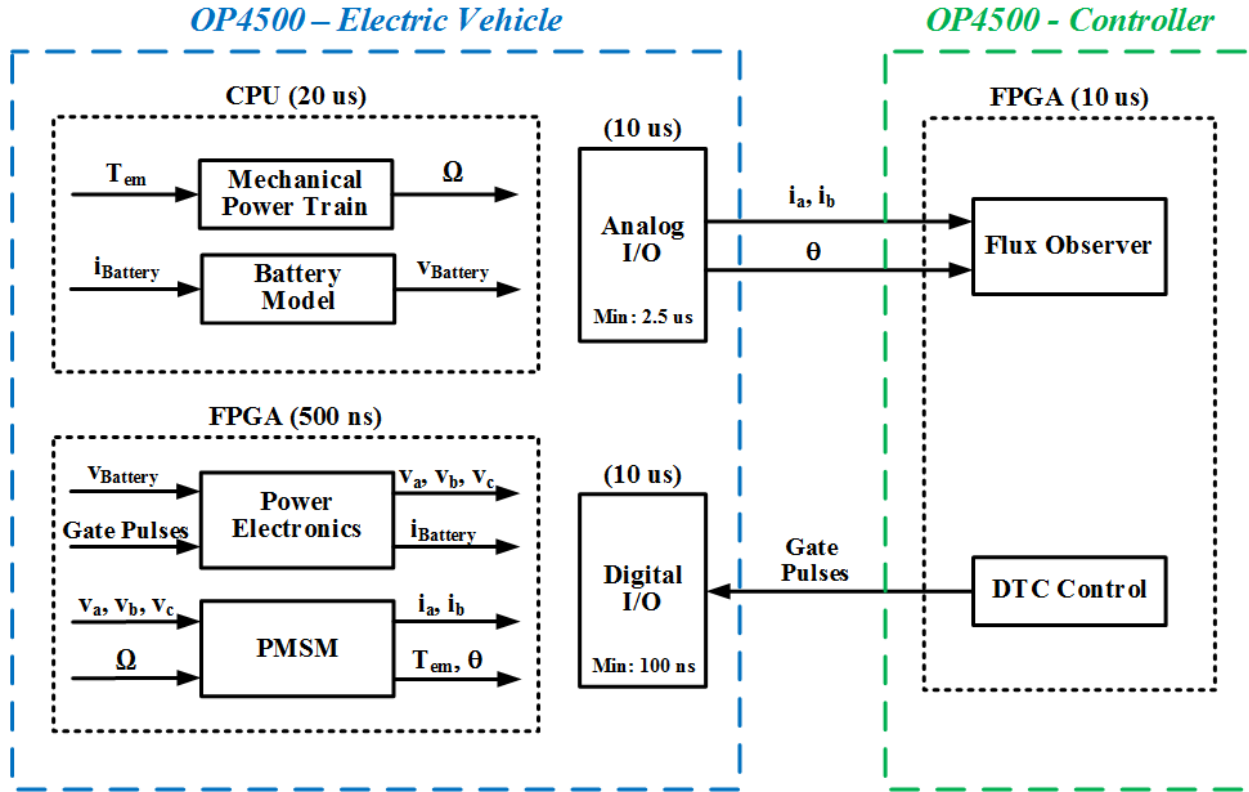


Figure 7: HIL Real-Time Simulation

The “Dual PMSM Motors VDQ” and “eHSx64 CommBlk” blocks are running on the real-time simulator FPGA at a rate of 500ns, as they simulate the electrical equations of the PMSM motor and the two-level three-phase inverter circuit, respectively. The battery and the mechanical power train are simulated on the real-time simulator CPU at a rate of 20 μ s.

The “Analog IO” subsystem monitors the analog outputs to be sent to the DTC controller real-time simulator, namely, the motor currents I_a and I_b and the electric rotor angle θ_e used for flux estimation. Furthermore, when moving to PHIL simulation, presented in subsection 3.2, the “Analog IO” block monitors the battery current sent to the amplifier as well as the battery voltage received from the amplifier.

The first simulation corresponds to the case where the vehicle accelerates until the speed reaches 80km/h at 38s, then the vehicle goes on a slope of 8% at 39.5s. The motor entities, namely, currents I_a, I_b and I_c , voltages V_{ab}, V_{bc} and V_{ca} , as well as vehicle speed and electromagnetic torque are given in Fig. 8. The stator flux, namely, $\psi_\alpha, \psi_\beta, \|\psi\|$ as well as the flux sector are depicted in Fig. 9.

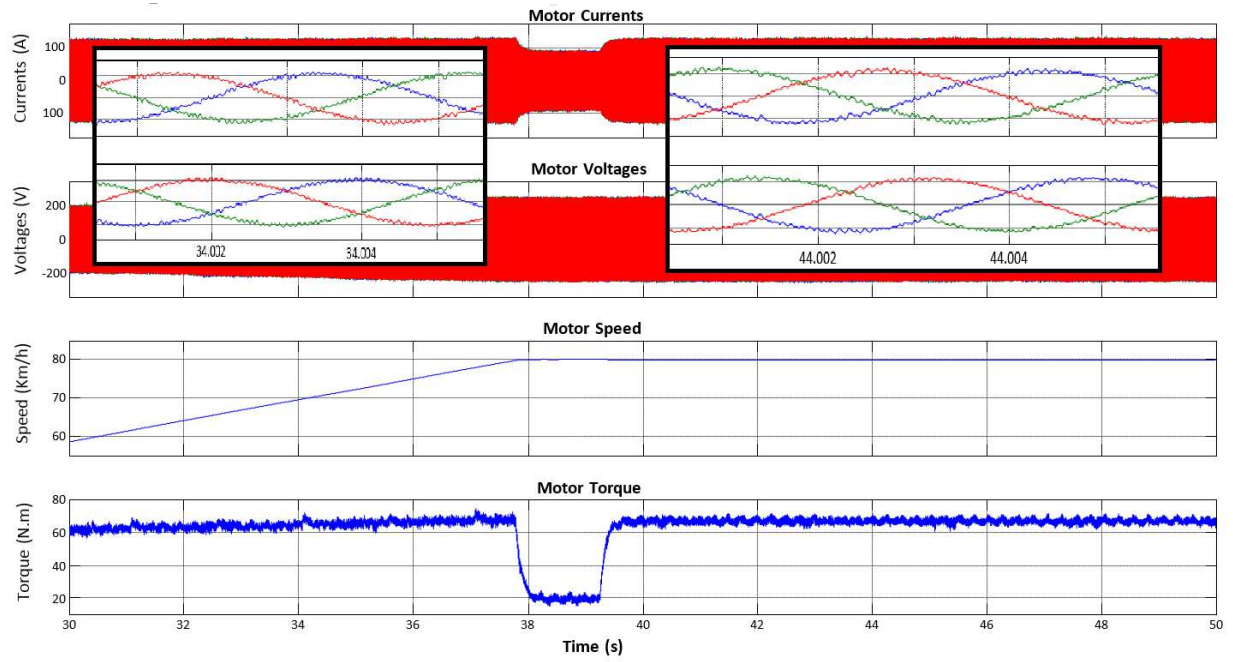


Figure 8: Motor currents, voltages, speed and torque

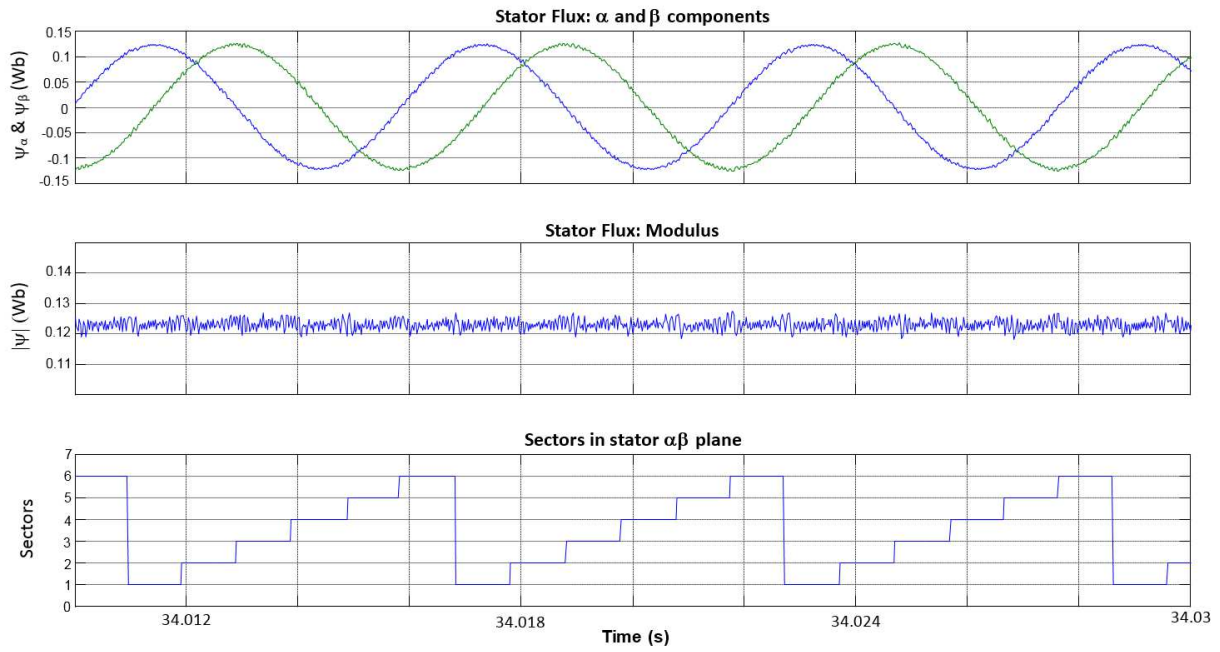


Figure 9: Stator flux and Sectors

The second simulation corresponds to the case where the vehicle accelerates until the speed reaches 80km/h at 33.5s, then at 35s it starts decelerating to 50km/h. The same motor entities are shown as before, together with battery current and voltage in Fig. 10.

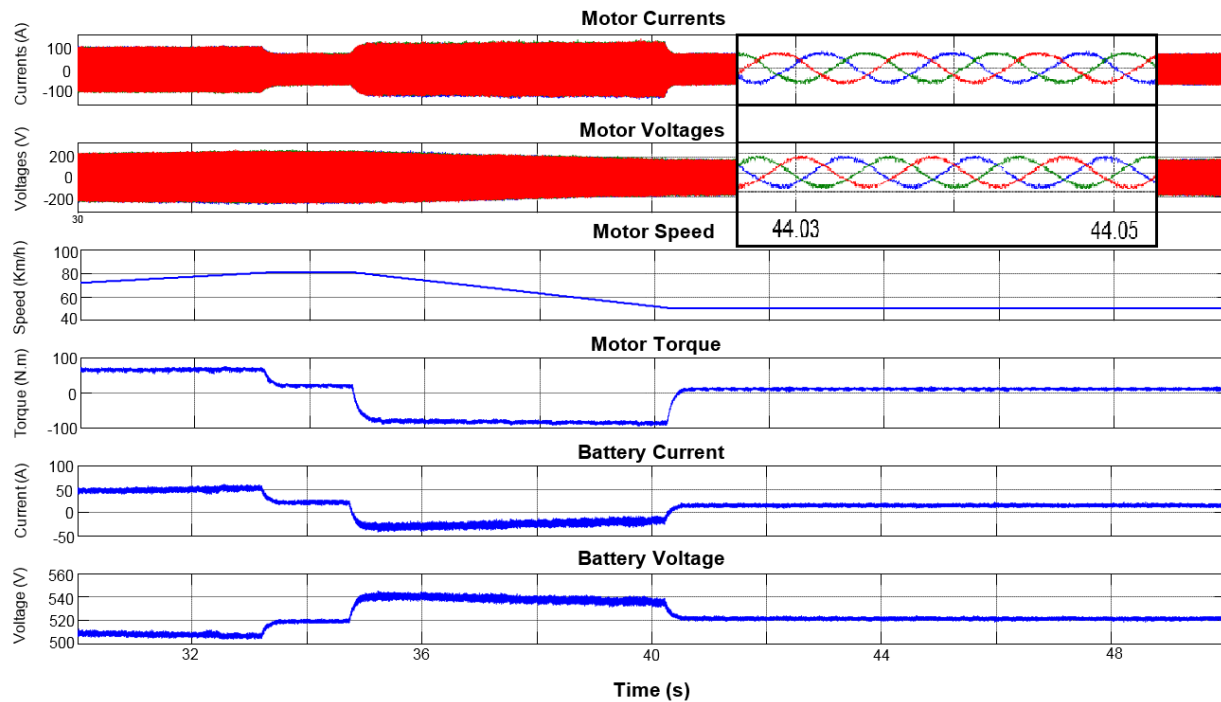


Figure 10: Motor currents, voltages, speed and torque, battery current and voltage

The third simulation corresponds to the case where the vehicle incurs a fault at 31.8s while accelerating to a speed of 80km/h. Motor currents and voltages, as well as battery current and voltage are shown in Fig. 11.

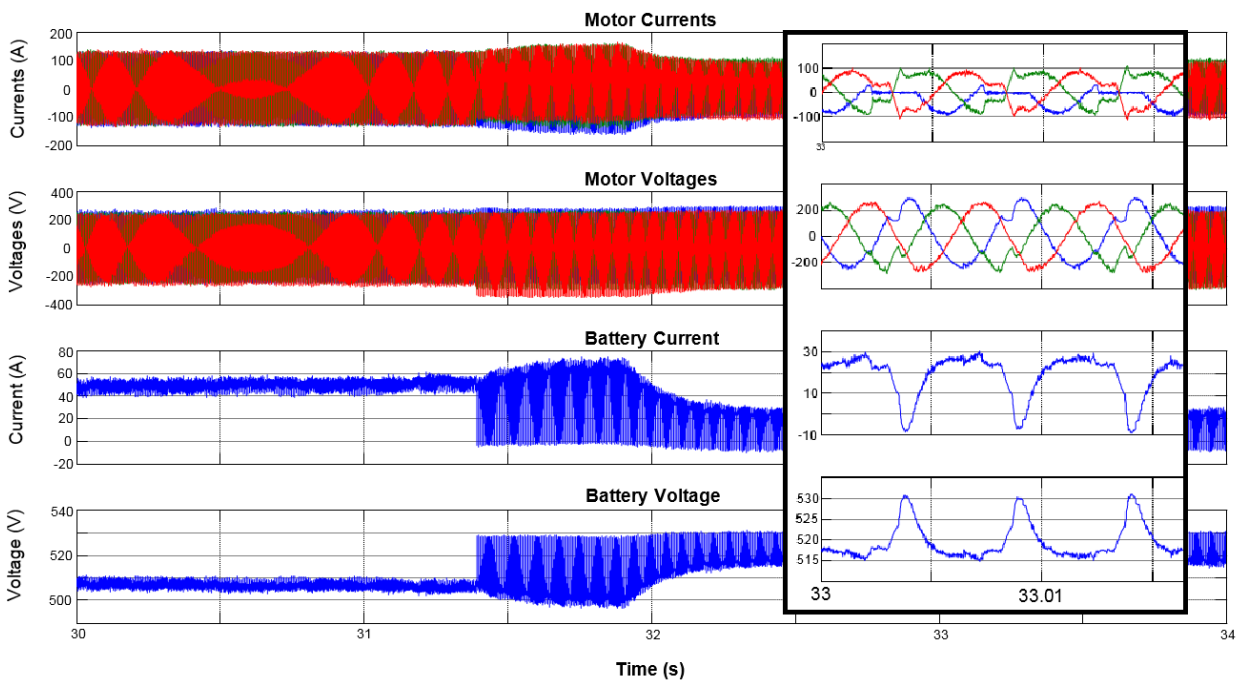


Figure 11: Motor and battery currents and voltages

3.2 Power-HIL Simulation

This setup replaces the battery model by a real physical battery cell, to be multiplied by the number of cells composing a complete battery pack. This PHIL battery simulation does not take into account non-uniformed temperature in one pack, thus considering all battery cells to have an equivalent response to the current that is being drawn. The PHIL simulation principle is shown in Fig. 12. As illustrated in Fig. 1, a current amplifier is driven by the real-time simulator's analog output, which calculates the battery current while the battery voltage sent back to the simulator is taken from the real battery voltage measurement.

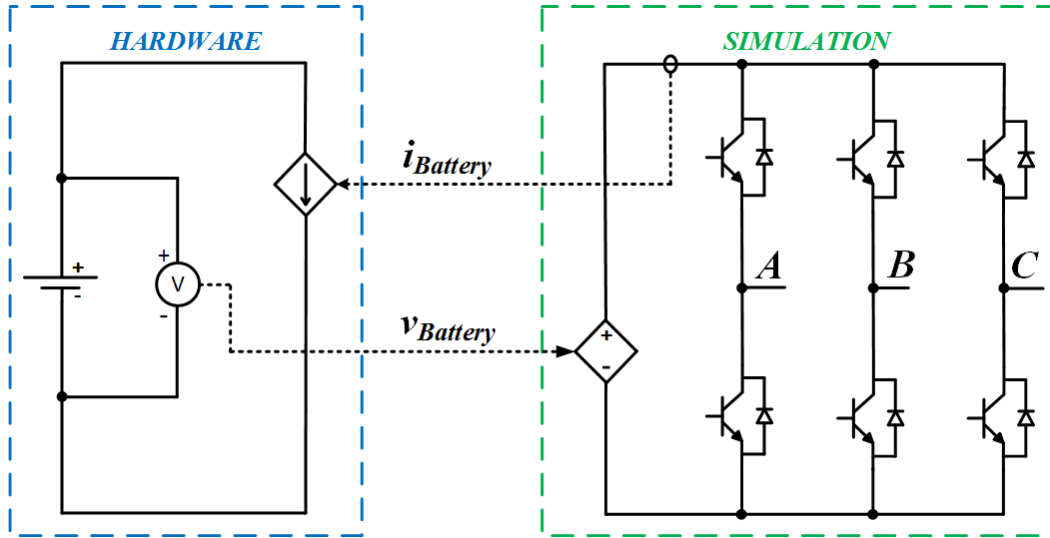


Figure 12: PHIL Principle - Use of a battery

Figure 13 shows the battery voltage obtained from HIL and PHIL simulations, as well as the battery current and the vehicle speed. It is noteworthy that current and voltage responses to speed variation respect the expected charge and discharge of the battery. Moreover, the slight difference between PHIL and HIL results are due to the fact that the battery parameters in HIL are constant and do not take into account the changes of operating conditions, while the PHIL deals with the real varying battery parameters.

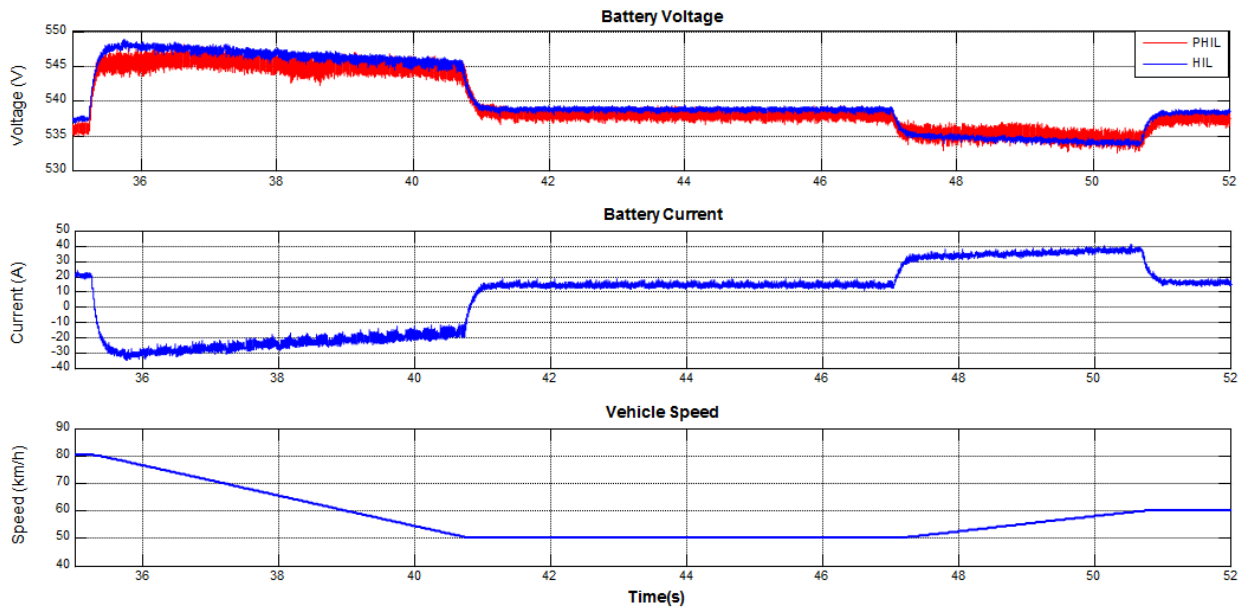


Figure 13: HIL and PHIL battery voltage and current and motor speed

Figure 14 shows the same PHIL entities as in Fig. 13, except with a fault provoked at 31.9s. This fault consists of keeping the upper IGBT of the first phase of the inverter open, thus giving the possibility to test the impact of a fault on real battery cell. Of course, no short-circuit test across the actual battery has been made for security reasons, but this test can be done in HIL simulation mode if the battery model is still valid for such case.

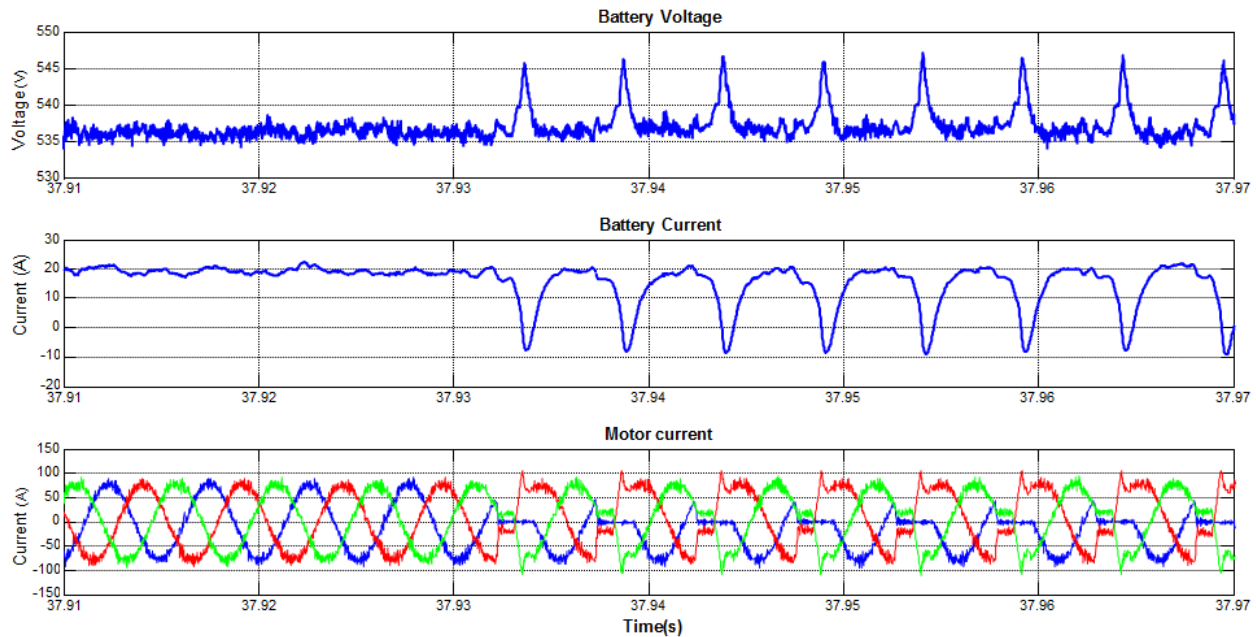


Figure 14: PHIL Battery voltage and current and motor currents

4 Conclusion

This paper presents HIL and PHIL methods now used by advanced power electronic manufacturers and R&D centers to accelerate design and testing of complex motor drives and reduce time-to-market.

High-fidelity HIL testing and RCP are now possible using fast FPGA/CPU-based real-time simulators capable of simulating power electronics converters with time steps ranging from 200ns to 500ns.

HIL controller testing should be used to test controllers and protection logic implemented in prototypes or production-grade engine control unit (ECU) hardware. HIL ECU testing enables evaluation of the controller and protection system performance under steady-state, transient and fault conditions that would be difficult or risky to perform with the real hardware.

Moreover, adding the real battery in PHIL mode increase the simulation accuracy since the mathematical model is replaced by the real battery. This may save development time and cost since there is no need to thoroughly test the battery to identify the battery model. By using the real battery we obtain better precision when prototyping and testing controllers if the variations of ambient temperature on battery performance are neglected.

Furthermore, PHIL can be used to accurately identify battery models of different battery types for several operating conditions. These validated battery models can then be used for HIL simulation (no real battery) by several engineering teams to concurrently develop and test several aspects of the controllers, motors and car dynamics using different types of batteries and operating conditions. Concurrent development using HIL simulation with validated battery models will then reduce development and testing time as well as time-to-market, since the use of expensive laboratories including the actual battery running at full power can then be decreased.

References

- [1] C. Dufour, S. Cense, T. Yamada, R. Imamura and J. Blanger, “FPGA Permanent Magnet Synchronous Motor Floating-Point Models with Variable-DQ and Spatial Harmonic Finite-Element Analysis Solvers”, *Proc. 15th International Power Electronics and motion Control Conference, EPE-PEMC 2012*, Novi Sad, Serbia, Sept. 4-6, 2012.
- [2] Y. Inaba, S. Cense, T. Ould-Bachir, H. Yamashita and C. Dufour, “A Dual High-Speed PMSM Motor Drive Emulator with Finite-Element Analysis on FPGA chip with Full Fault Testing Capability”, *Proc. 14th European Conference on Power Electronics and Applications, EPE 2011*, Birmingham, UK, Aug. 30-Sept. 1st, 2011.
- [3] P. Pejovic and D. Maskimovic, “A Method for Fast Time-Domain Simulation of Networks with Switches”, *IEEE Trans. Power Electronics*, vol. 9, No. 4, July 1994.
- [4] C. Depature, P. Sicard, A. Bouscayrol, W. Lhomme and L. Boulon, “Comparison of Backstepping Control and Inversion-Based Control of a Range Extender Electric Vehicle”, *Proc. IEEE Vehicle Power and Propulsion Conference, VPPC 2014*, Coimbra.
- [5] J. Jaguemont, L. Boulon and Y. Dub, “Characterization and Modeling of a Hybrid-Electric-Vehicle Lithium-Ion Battery Pack at Low Temperatures”, *IEEE Trans. Vehicular Technology*, vol. 65, No. 1, pp. 1-14, Jan. 2016.
- [6] M. Lemaire, P. Sicard and J. Belanger, “Prototyping and Testing Power Electronics Systems Using Controller Hardware-In-the-Loop (HIL) and Power Hardware-In-the-Loop (PHIL) Simulations”, *Proc. IEEE Vehicle Power and Propulsion Conference, VPPC 2015*, Montreal, QC.
- [7] P. Vas, *Sensorless Vector and Direct Torque Control*, Oxford University Press, 1998.
- [8] C. Bian, S. Ren and L. Ma, “Sensorless DTC of Super High-Speed PMSM”, *Proc. IEEE International Conference on Automation and Logistics*, Jinan, China, Aug. 18-21, 2007

Authors

Danielle Sami Nasrallah received the Engineer’s diploma in electromechanical engineering and the Diplôme d’Études Approfondies in electrical engineering from École supérieure d’ingénieurs de Beyrouth (ÉSIB), Beirut, Lebanon in 2000 and 2002, respectively, and the Ph. D. degree in mechanical engineering from McGill University, Montréal, QC, Canada, in 2006.

During her Ph. D. studies she worked on a part-time basis at Robotics Design as control and robotics engineer. She moved to Meta Vision Systems in 2006-2007 as a control and applications engineer.



In 2008 she joined the electrical department of the Royal Military College of Kingston as an assistant professor and, in 2009, she was a visiting assistant professor at the American University of Beirut. From 2010 to 2014, she worked as a consultant in control and systems engineering. In 2014 she joined OPAL-RT Technologies where she is presently an expert in electrical applications and simulation. She kept also links with academia as she is a lecturer in the department of mechanical and industrial engineering at Concordia University.

Michel Lemaire received his B.S. degree in Electrical engineering at the Université du Québec à Trois-Rivières (UQTR), QC, Canada, with a specialization in power systems at the Electrical Energy Engineering Institute in 2014. He is presently pursuing his M.S. degree in the same field, supported by an Opal-RT Technologies-NSERC-FRQNT Industrial Innovation Scholarship. Past work includes Hardware-In-the-Loop (HIL) of automotive apparatus, motor emulation and grid emulation based on Power Hardware-In-the-Loop (PHIL) simulation and four quadrant amplifier design. His research interests include Power Hardware-in-the-loop and Hardware-in-the-loop system, real-time simulation, control and power electronics.





As president and R&D Director, Mr. Jean Bélanger defines the vision and corporate direction of Opal-RT technologies and steers its efforts in research and development. Prior to co-founding Opal-RT in 1997, he worked at Hydro Quebec for 25 years, where he was one of the main design engineers of the 765 kV James Bay transmission system. In 1978, he led the commercialization of Hydro-Quebec's simulation services around the world, designing and promoting Hydro-Quebec's electric network simulator. Taking up an area of 10,000 ft² and costing \$14M, this unique simulation facility is still the world's largest and most sophisticated real-time large-scale electrical network simulator. Mr. Bélanger also promoted the sale of electric network simulators. From 1993 to 1996, he designed and delivered several large-scale simulators to a number of leading companies worldwide, including Mitsubishi, Hitachi, Toshiba and EPRI (China). Subsequently, he co-founded TEQSIM, the Hydro-Quebec subsidiary dedicated to the commercialization of real-time simulation technologies. Over the course of his distinguished career, Mr. Bélanger has actively participated in, and served as President at numerous ACE (Association Canadienne de l'Électricité) and CIGRE (Conférence Internationale des Grands Réseaux Électriques) events. Mr. Bélanger is an electrical engineer (Université Laval, Québec) with a Masters degree in Power Systems from École Polytechnique de Montréal. He was recently named member of the Canadian Order of Engineers, an organization with a membership limited to only 250 persons.



Loïc Boulon received the master degree in electrical and automatic control engineering from the University of Lille (France), in 2006. Then, he obtained a PhD in electrical engineering from University of Franche-Comté (France). In 2009 and 2010, he was a postdoctoral researcher at University du Québec à Trois-Rivières (UQTR, Canada).

Since 2010, he is a professor at UQTR and he works into the Hydrogen Research Institute. His work deals with modeling, control and energy management of multiphysics system. His research interests include hybrid electric vehicles, energy and power sources (especially battery in cold weather operation), and fuel cell systems. He has published more than 100 scientific papers in peer-reviewed international journals and international conferences. In 2015, Loïc Boulon was general chair of the IEEE-Vehicular Power and Propulsion Conference in Montreal (QC, Canada). Prof. Loïc Boulon is VP-Motor Vehicles of the IEEE Vehicular Technology Society and the holder of the Canada Research Chair in Energy Sources for the Vehicles of the future.