

A Novel Platform for Power Train Model of Electric Cars with Experimental Validation Using Real-Time Hardware in-the-Loop (HIL): A Case Study of GM Chevrolet Volt 2nd Generation

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Abstract— This paper presents a novel platform for accurate mathematical modeling of electric cars' propulsion system. It provides, for the first time, a Hardware in-the-Loop (HIL) real-time experimental verification for a case study of GM Chevrolet Volt for both power and control parts in addition to the mechanical part. The novelty of this work can be split into three steps; first, each component of the power-train is accurately modeled taking transient dynamics of all parts of the electric vehicle (EV) into consideration. Secondly, a PSIM simulation platform is consequently developed, to demonstrate the validity of this mathematical modeling. Finally, the Typhoon HIL is used to provide the experimental verification of the proposed model in real-time, which precisely validate the viability of the model. The HIL technology is used to prototype and test the control proposed system while simulating the power circuit on the HIL module platform. The Permanent Magnet Synchronous Motor (PMSM) and the Power Electronics hardware components are simulated in real-time at which the parameters can be changed while the simulation is running. However, the control algorithm is generated as a C code and downloaded to the TI controller that exists on a Digital Signal Processing (DSP) board. The results from the simulation based on PSIM environment and hardware validations using HIL are in agreement, which validates the developed model. The performance has been investigated under different load operating conditions in real-time to verify its robustness. The case study can be extended for any electric car as it provides a generic platform for modeling any propulsion system.

Keywords – Hybrid Electric Vehicles (HEVs), Permanent magnet synchronous motor (PMSM), Power Electronics (PEs), Real-time Simulation, Hardware in-the-Loop (HIL), PSIM, Digital Signal Processing (DSP).

I. INTRODUCTION

With the Paris climate agreement coming into effect, all civilized solidities have a mandate to limit the carbon foot print of electric vehicles. Consequently, many countries around the world, adapt more stringent standards in terms of mitigating fuel exhaust. As a result of this universal pressure, the automotive industry came under the scope to deploy carbon emission-free electric cars [1-3]. The main contribution of this paper is to develop a generic

platform to successfully model any HEVs or EVs. The model is mathematically developed and simulated using PSIM software package. A case study using real data of GM Chevrolet Volt is adopted in this paper to reveal the model viability. The energy performance of the Chevy Volt can be evaluated from three different areas: propulsion system, battery charging and discharging control, and the vehicle mechanical design [4], [5]. The propulsion system of any HEV consists of two main machines. One of them is working most of the time as a motor and the other one is working as a generator that is being driven by a combustion engine. The propulsion system of the Chevy Volt, in particular the HEV version, is quite complicated and that was one of the major reasons for selecting this car to be the main focus of this work where designing and implementing its model will open the door for more achievements in enhancing the performance of any powertrain of other vehicles [6-9]. The HEV version is more inclusive to the EV version, when it comes to modeling. This is the main reason behind selecting this version. In this paper, a profound and detailed mathematical model of a HEV, taking into consideration system dynamics through controlling different state variables, has been performed and a simulation schematic has been accomplished using PSIM software platform. However, in order to verify the simulation results in real time, a Hardware in-the-Loop (HIL) experimental emulation has been used [10], [11].

The HIL provide a way to test and verify the control algorithms in real time through virtualizing the vehicle hardware. Saving cost and time with high fidelity, the HIL technology affords a method by which the vehicle model can be investigated under a variety of a bunch of realistic potential scenarios. The HIL topology used in this work is shown in Fig. 1. Fig. 2 depicts the interface between power and control circuits [12]. The HIL, used in this work, consists of the main module HIL402 and the Digital Signal Processor (DSP 100) and the TI controller (TMS320F28335). The processing power of DSP controller is allowing the accurate

control of power converters. Therefore, they provide an appealing solution for design validation. It is important to mention that this is the first time that the Typhoon HIL is used in automotive design research applications. This adds more depth to the novelty of the proposed work. Typhoon HIL is widely used for smart grid applications but this work proves its capacity to include new areas of research. One of the main objectives of the proposed work is to implement the HIL testing, from scratch, on the Chevy Volt model and verify the simulation results obtained with PSIM. This paper is arranged as follows: Section II provides the mathematical model details of the electrical component. Section III demonstrates the simulation results obtained from the PSIM model. However, section IV, illustrates the HIL environment and how the PSIM model has been mapped to the HIL platform. Finally, section V concludes the main ideas and depicts the benefits of this work.

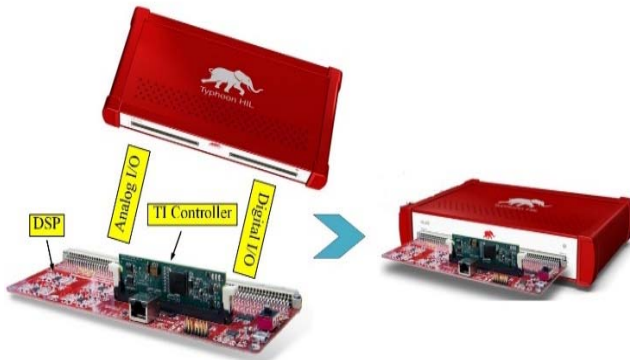


Fig. 1. HIL controller topology

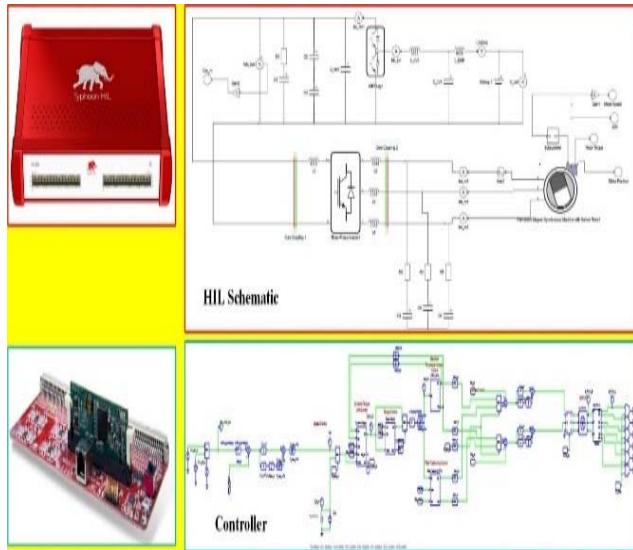


Fig. 2. Interface between power circuit in HIL platform and control circuit coded and downloaded to the DSP board

II. SYSTEM MODELING

1. ELECTRICAL MATHEMATICAL MODELING

This mathematical model can be used for describing the dynamics of the permanent magnet synchronous machine with a salient rotor. The model assumes that the stator flux linkage established by the permanent magnets is sinusoidal, which implies that the electromotive forces are sinusoidal. The electrical part of the machine is represented by a second-order state-space model in a synchronously rotating dq reference frame, invariant to the electrical variable amplitudes, as described in [13]. The dq reference frame is attached to the rotor, and the d-axis is aligned with the rotor magnets. The modeled dynamic can be represented with following equations:

$$\frac{d}{dt} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r \\ -\omega_r & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} + \begin{bmatrix} 1 & 0 & \frac{R_s}{L_d} \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ \lambda_{PM} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} + \begin{bmatrix} 0 & 0 & -\frac{1}{L_d} \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ \lambda_{PM} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} \\ -\frac{1}{3} & \frac{1}{3} \\ -\frac{1}{3} & -\frac{2}{3} \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_{ab} & \cos(\frac{2\pi}{3} - \theta_{ab}) & \cos(\frac{2\pi}{3} + \theta_{ab}) \\ -\sin\theta_{ab} & \sin(\frac{2\pi}{3} - \theta_{ab}) & -\sin(\frac{2\pi}{3} + \theta_{ab}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (5)$$

Output stator current dq - components are transformed back to the stationary reference frame $\alpha\beta$ -components using an inverse Park transformation in the following form:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (6)$$

Stator current $\alpha\beta$ -components are transformed to phase values using an inverse Clarke's transformation:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta_{ab} & -\sin\theta_{ab} \\ -\cos(\frac{2\pi}{3} + \theta_{ab}) & \sin(\frac{\pi}{3} + \theta_{ab}) \\ -\cos(\frac{2\pi}{3} - \theta_{ab}) & -\sin(\frac{\pi}{3} - \theta_{ab}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

2. MECHANICAL MATHEMATICAL MODELING

The basic equations of the mechanical system of the machine can be represented by a second-order state-space model [19]:

$$\frac{d}{dt} \omega_m = \frac{1}{2J_m} (T_e - T_L) \quad (8)$$

$$\frac{d}{dt} \theta_m = \omega_m \quad (9)$$

$$T_e = \frac{3}{2} p (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (10)$$

2.1 Vehicle Dynamics

Modeling the vehicle dynamics is so crucial to calculate the required power demand by the wheels to meet the instantaneous driving conditions. Also, calculating the forces acting on the vehicle while moving, such as the aerodynamic drag force, the rolling resistance and the grading resistance which are classified under the resistive forces category as well as the propelling force, is of great importance to accurately and precisely determine the required wheel power demand.

The longitudinal vehicle dynamics can be modeled based on the following equation:

$$m_c a_c = F_T - (F_{dr} + F_R + m_c g \sin \delta) \quad (11)$$

Equation (12) is used to obtain the power demand of the vehicle wheels:

$$P_d = V_C F_T = V_C (m_c a_c + F_{dr} + F_R + m_c g \sin \delta) \quad (12)$$

Where

$$a_c = \frac{v(t+\Delta t) - v(t)}{\Delta t}$$

$$F_{dr} = \frac{1}{2} \rho V_C^2 A_f C_{dr}$$

$$F_R = m_c g \cos(\delta) C_r$$

III. SIMULATION RESULTS

The implementation proposed model depicted in Fig. 3 has been tested on PSIM and the simulation results of the 3-phase line currents are shown in Fig. 4 that show nearly sinusoidal waveforms in the zoom-in view. The PMSM rotor speed shown in Fig. 5 is shown to be constant at 2014 rpm while the average value of the vehicle torque displayed in Fig. 6 is 56 N.m.

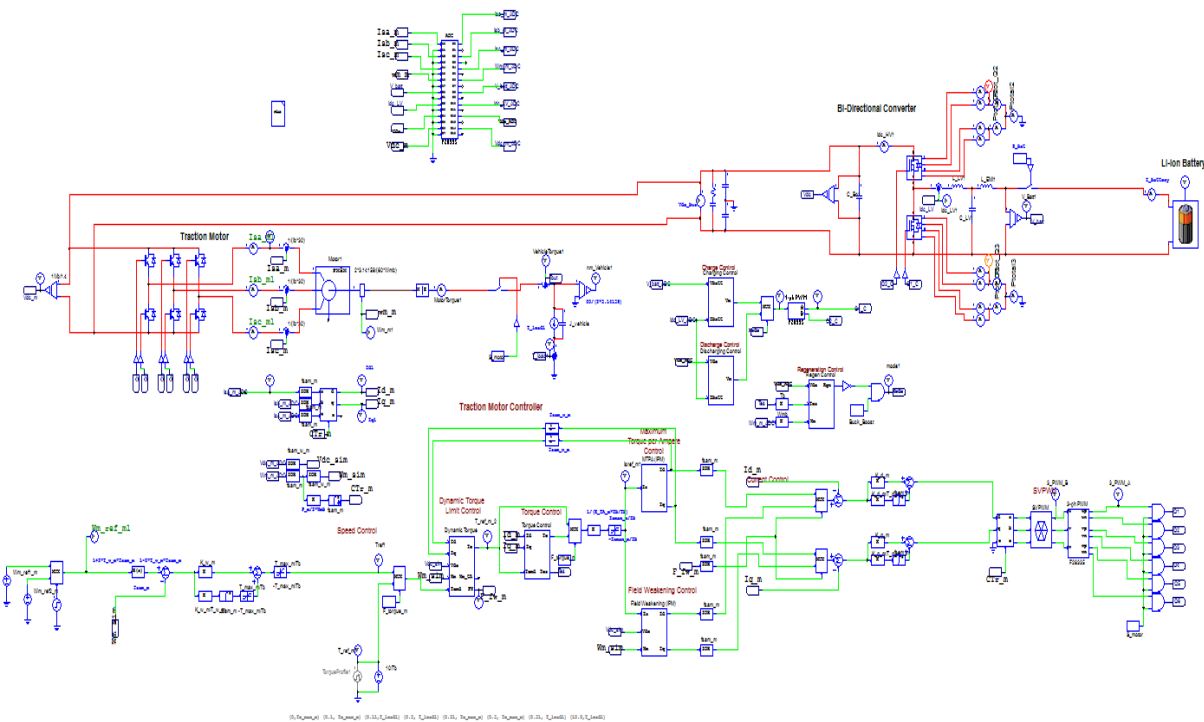


Fig. 3. Implementation of EV in PSIM (Schematic diagram)

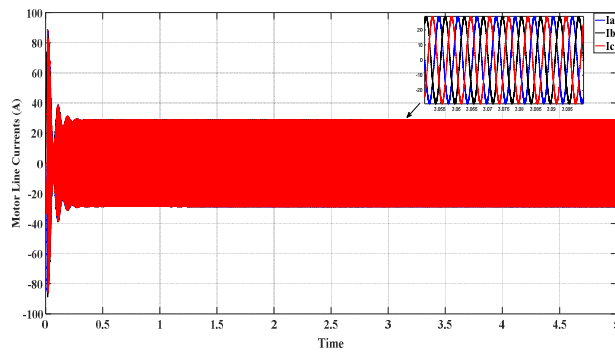


Fig. 4. The 3-phase line currents of the PMSM motor

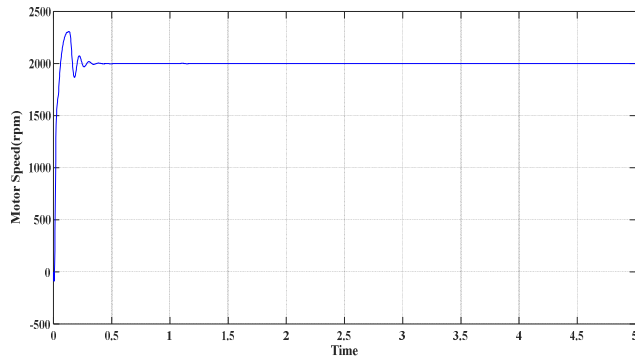


Fig. 5. The motor speed in (rpm)

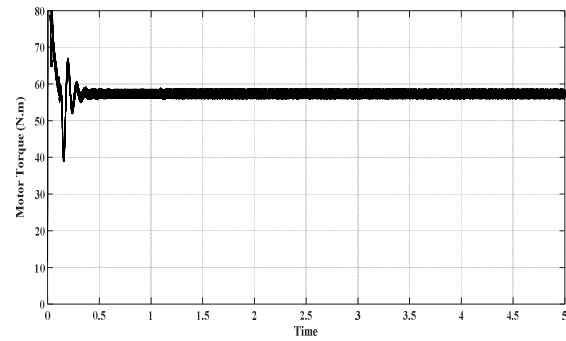


Fig. 6. The motor torque in (N.m)

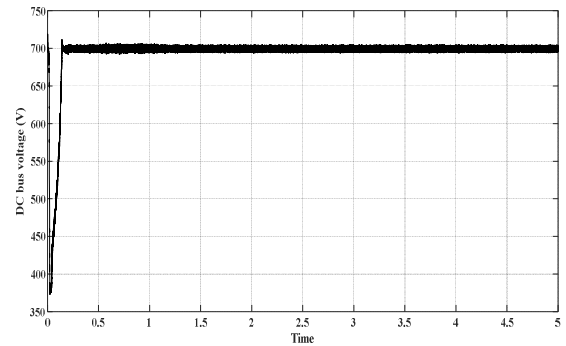


Fig. 7. The DC bus voltage

IV. HARDWARE IN-THE LOOP (HIL) EXPERIMENTAL VERIFICATION

The HIL system consists of the powertrain loop while the control loop is simulated in the computing platform on PSIM and the link between the two circuits is via the Analog to Digital converter (TI FX28335 ADC). The controller behavior can be validated at various environmental conditions and the controller robustness can be tested by introducing powertrain component and subsystem malfunctions. With HIL, we can identify and resolve problems earlier in the development cycle. There are some requirements for the HIL implementation that should be satisfied in order to ensure accurate results. These requirements include that the system should have fidelity so that the controller malfunctions are only triggered with the same settings as in the vehicle. An interface with the controller physical signals should be provided to enable modifications when required. Fig. 8 shows the HIL set-up which contains the HIL module, the oscilloscope and the HIL power circuit model on Typhoon HIL software. The control circuit code is generated from PSIM and converted to C code using Code Composer Studio software then downloaded on the TI controller.

The Typhoon HIL plays a role of an interface between power circuit and the downloaded control code. The schematic and the controller are shown in Fig. 9. Figs. 10 and 11 show the HIL results panel obtained at the beginning and after 5 seconds of the simulation respectively. Figs. 12 to 15 show the HIL results correlate to a high degree with the PSIM simulation results. This proves the sound accuracy of the developed model.

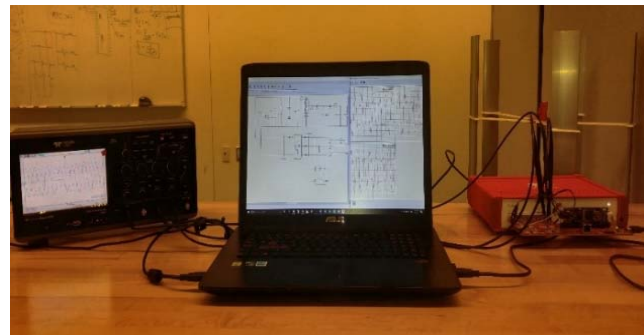


Fig. 8. Hardware in-the-Loop test bench

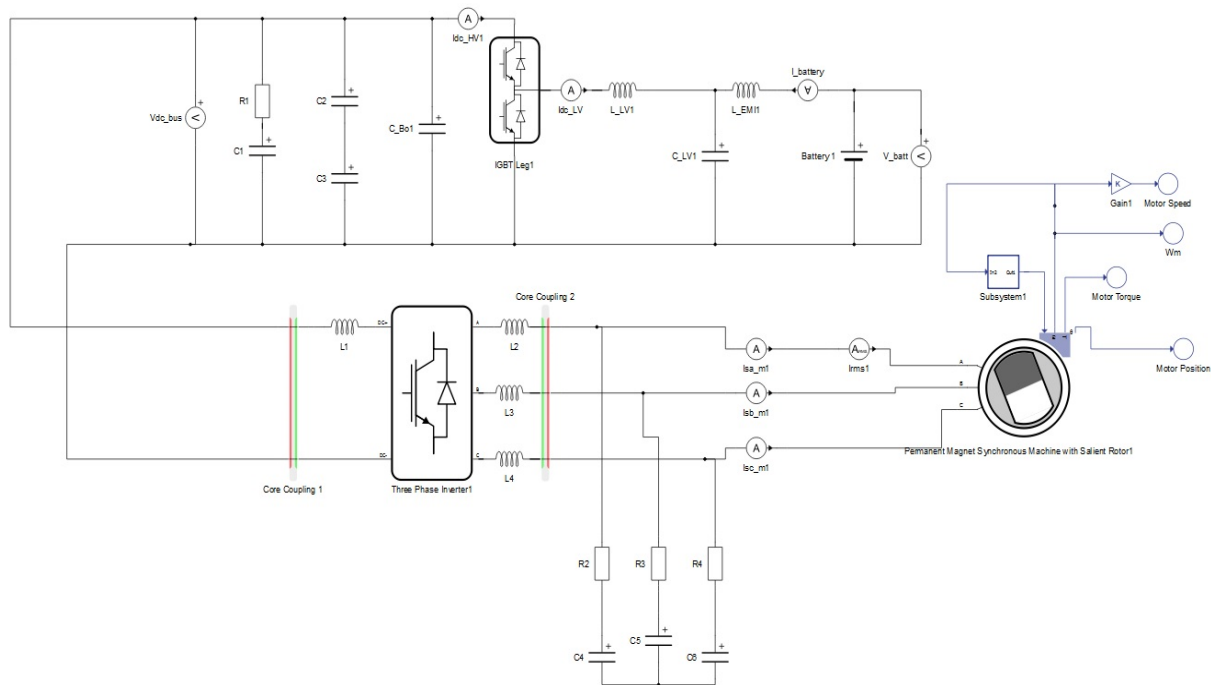


Fig. 9. The Typhoon HIL power circuit schematic



Fig. 10. Motor speed, DC bus voltage, Battery current, Battery voltage, RMS of the motor line current, and motor torque obtained in real-time HIL simulation after 5 secs.

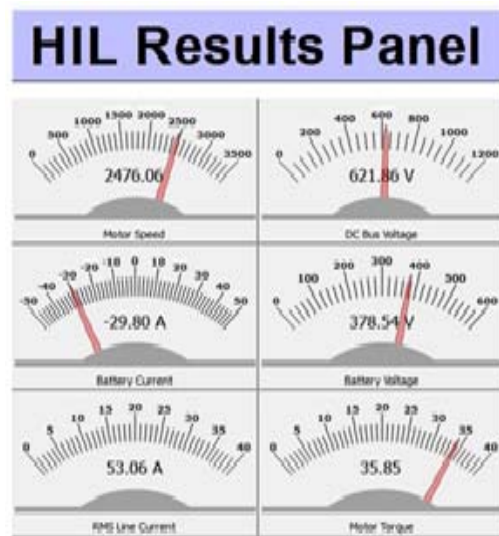


Fig. 11. Motor speed, DC bus voltage, Battery current, Battery voltage, RMS of the motor line current, and motor torque obtained in real-time HIL simulation at the beginning.

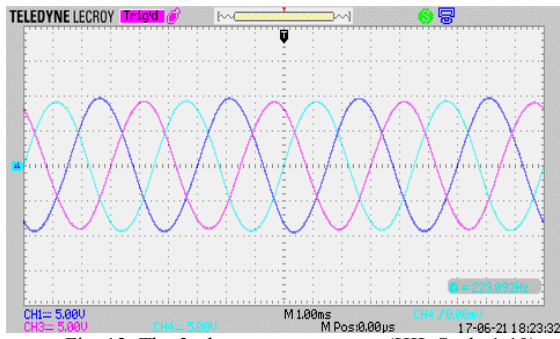


Fig. 12. The 3-phase motor currents (HIL Scale 1:10)

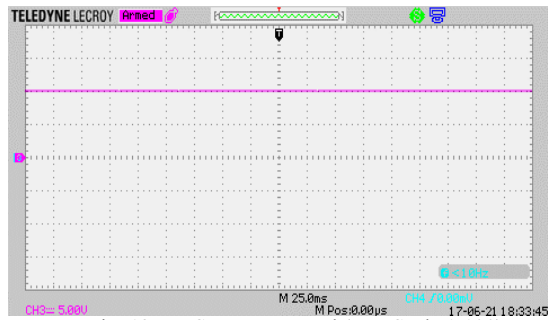


Fig. 13. PMSM Rotor speed (HIL Scale 1:100)

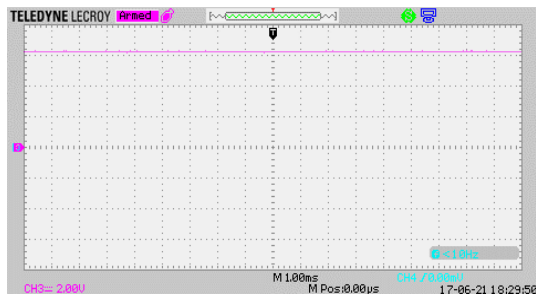


Fig. 14. DC Bus Voltage (HIL Scale 1:100)

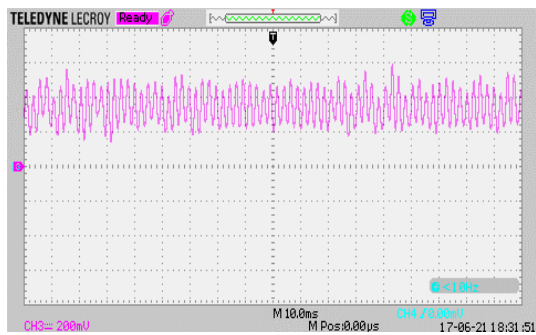


Fig. 15. Motor Torque (HIL Scale 1:100)

For the purpose of making a comparison between the results obtained from the simulation results and the results obtained from

the Typhoon HIL, Figs. 16 and 17 are shown below. Fig. 16 depicts the motor torque achieved from the simulation results, shown in red, in comparison with the motor torque output extracted from the Typhoon HIL module. It can be shown that the torque is oscillating in the beginning then settled to a normal average value of 57 N.m. The average value is obtained directly from the HIL module at steady state as the time of the transient period is too small to be captured. Also, in Fig. 17, the engine speed is being compared in order to verify the mechanical modeling and its performance.

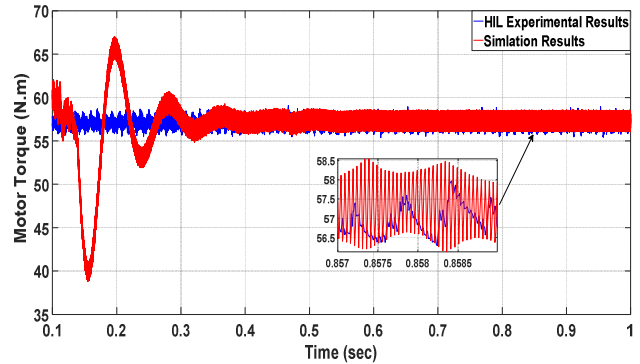


Fig. 16. Comparison between the Motor torque obtained from the HIL emulation and that one obtained from the simulation results

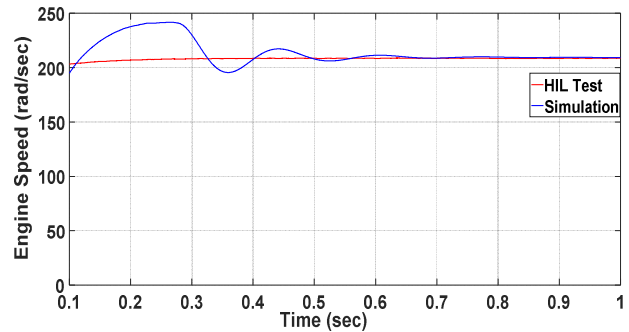


Fig. 17. Comparison between the Motor torque obtained from the HIL emulation and that one obtained from the simulation results

V. CONCLUSION

In this paper, a case study of complete HEV model has been set up for the purpose of testing the power-trains of many types of vehicles. A hardware in-the-Loop is used to represent the experimental verification of the proposed model. The control algorithm implemented on a dedicated DSP of the HIL system is tested in real-time with the system power circuit built in the HIL environment. The behaviors of the different system components are studied. The results gained from PSIM and HIL testing reveal a very close agreement which demonstrate clearly the

effectiveness of the mathematical model based on real data obtained for the Chevy Volt HEV. This work provides a platform to test and model any design for a propulsion system for different electric vehicles. It is worth mentioning that this approach fits the need and can be expanded to model electric trains and planes.

VI. REFERENCES

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