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Implementation of Electric Vehicle Hardware-in-the-Loop Test Platform

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Abstract

This paper presents a finite element model-based real-time simulation system for the permanent magnet synchronous motor (PMSM) driving system, which, in combination with the vehicle kinetic model, forms a complete electric vehicle (EV) hardware-in-the-loop (HIL) simulation and test platform. The software JMAG is used to establish the PMSM finite element model, and the platform of field-programmable gate array (FPGA) is adopted to construct the PMSM real-time simulation model. The finite element model is also retrieved to coordinate with the vehicle kinetic model in order to facilitate the testing and development of the controller of the EV, the matching of the driving system, the kinetics control algorithms, etc. Through comparing the real-time simulation of the motor driving system with the experimental results of the test bench, as well as analyzing the HIL simulation results of the entire vehicle model, this paper verifies the accuracy and effectiveness of this HIL simulation and test platform.

***Keywords**: EV; PMSM drive system; HIL; FEA*

1. Introduction

Since the beginning of the 21st century, the eventual exhaustion of oil resources and the increased oil prices have become a topic of global concern, and meanwhile, the rapid development of the traffic capacity has brought about more severe environmental pollution [1]. Characterized by zero emission and a sustainable source of energy, the electric vehicle is considered as an ideal alternative to conventional cars.

The development and the matching of the motor driving system are the focus of the research and development of electric vehicles. In this respect, offline simulation has many advantages. For instance, it is fast and low-cost. But it also has some obvious disadvantages, *i.e.*, its simulation results could not evaluate the real-time parameters of the motor driving system in real-time situation [2]. Therefore, in the traditional development environment, it is impossible to test the controller or carry out the dynamics matching verification before the completion of the electric-motor prototype. The hardware-in-the-loop (HIL) simulation, however, can solve all of these problems. HIL is a kind of real-time simulation technology which runs the simulation model using a real-time processor and simulates the motion state of the controlled object in conjunction with some hardware. It connects the under-test electronic control units (ECUs) or other peripheral devices through an I/O port and conducts a real-time test to the control strategies and control algorithms which are constructed. It could revert, to the greatest extent, to the working state when the vehicle actually runs and simulate the working situation of semi-physical systems in extreme conditions to verify the fault tolerant performance, reduce road test times, shorten the development period and decrease the R&D cost [3].

The difficulty in real-time simulating the motor driving system lies in the complexity of the system's mathematical model and it is difficult for traditional HIL devices to meet

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the real-time requirements of the simulation. In this paper, a PMSM finite element model is used to build the real-time simulation system for PMSM motors, inverters and vehicles in combination with FlexRIO Boards and PXI Systems provided by NI Corporation. Through simulating the details of work done by motors and inverters, such a system could test and verify the control strategies as well as the hardware performance of EV controllers and motor controllers, which could not only ensure the real time of the simulation but also make the simulation closer to the real work condition. This paper compares the simulation results obtained from this platform with the experimental results of the test bench of the motor driving system, and verifies the effectiveness of the HIL platform built in this paper.

2. The Overall Structure of Evs' HIL Test Platform

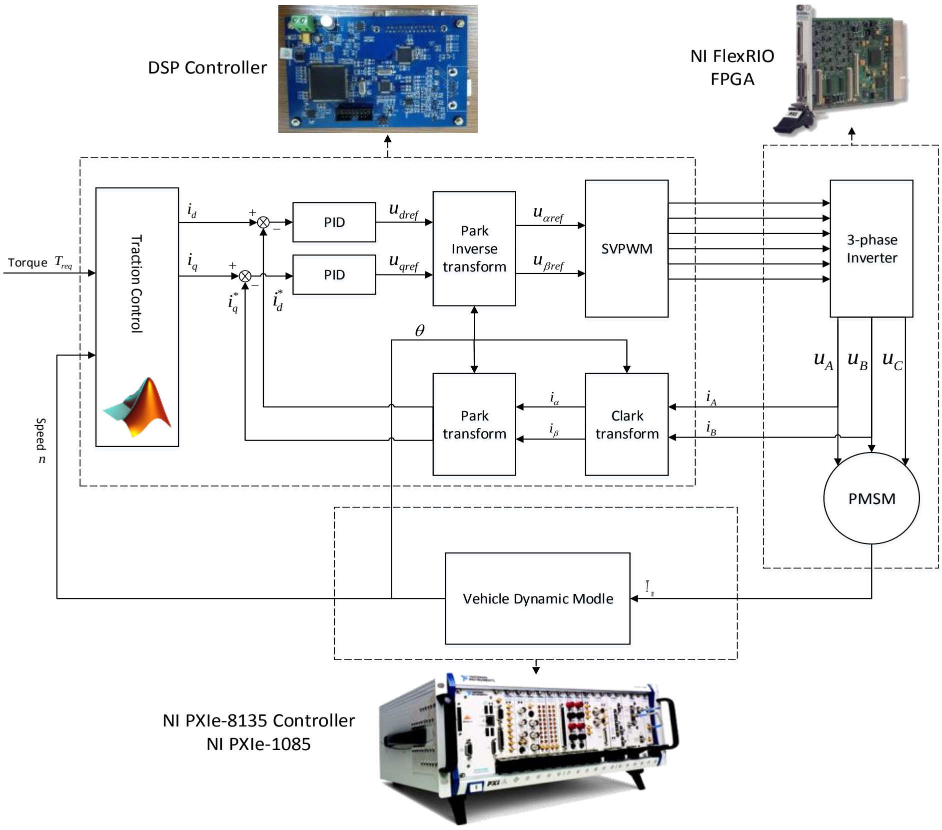

Figure 1. The Overall Structure of the HIL Test Platform

The overall structure of the HIL simulation and test platform built in this paper for electric vehicles is shown in Figure 1. It is made up of three parts including the real-time models of motor controllers and motor driving systems (models of PMSM and three-phase inverters) and the vehicle kinetic model.

The motor controller adopted in this paper is a prototype developed by the project team. Optimal control strategies and space vector pulse width modulation (SVPWM) are carried out to the motor. The TMS320F28335 chip from TI Corporation is taken as the controller of the prototype. Characterized by stronger floating-point operational capability, this DSP chip can collect the current and position signals sent out by the HIL system in real time situation, and output 6-channel PWM inverter IGBT gate driving signals to the inverter model after completing the optimal control strategies and the SVPWM algorithm to control the driving system of the motor.

The mathematical models of PMSM and three-phase inverter are built in the NI FlexRIO FPGA board. FPGA is the technology of field-programmable gate array, which is essentially the building of models in hardware description language and is highly real-timed. The specific modeling process of the motor driving system in the FPGA platform will be described in detail later in the following part.

The vehicle kinetic model are built on the NI PXIe platform. PXIe-8135 controllers, corresponding data acquisition and CAN communication boards, *etc.* are used for the real-time simulation of the model and its communication simulation with other modules of the HIL system.

3. Building the HIL System Model

3.1. The Mathematical Model of the Three-Phase Inverter

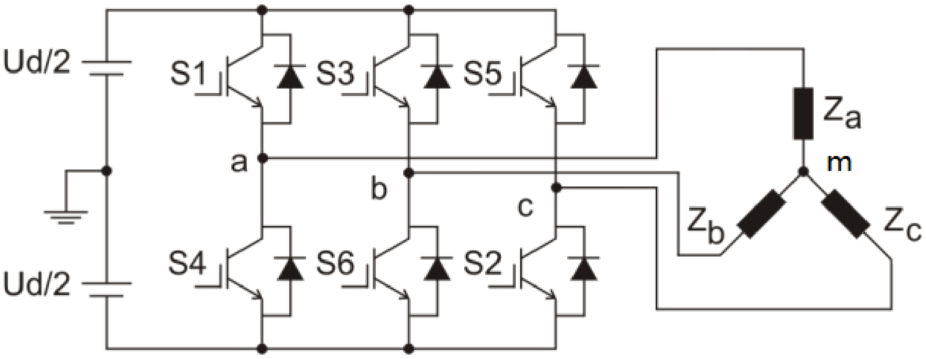

Figure 2. The Circuit of the Three-Phase Inverter

Figure 2 shows the circuit of a three-phase inverter. It is mainly made up of six high-speed switches, each two of which constitutes a bridge circuit. To facilitate the analysis and calculation [4], the upper arm and lower leg of each bridge circuit are described using the switching function $S_i\,(i = a,b,c)$ as follows:

$$S_a = \begin{cases} 0 & (S_1 \text{ turned off}, \ S_4 \textit{ turned on}) \\ 1 & (S_1 \textit{ turned on}, \ S_4 \text{ turned off}) \end{cases}$$
$$S_b = \begin{cases} 0 & (S_3 \text{ turned off}, \ S_6 \textit{ turned on}) \\ 1 & (S_3 \textit{ turned on}, \ S_6 \text{ turned off}) \end{cases} \tag{1}$$
$$S_c = \begin{cases} 0 & (S_5 \text{ turned off}, \ S_2 \textit{ turned on}) \\ 1 & (S_5 \textit{ turned on}, \ S_2 \text{ turned off}) \end{cases}$$

Provided that the PMSM motor is a star-connected three-phase load in the equivalent circuit, and the midpoint of the inverter is m, we can obtain:

$$U_{am} = \begin{cases} \dfrac{U_d}{2} & (S_a = 1) \\ -\dfrac{U_d}{2} & (S_a = 0) \end{cases} \tag{2}$$

Wherein, U_{am} is the a-phase output voltage of the inverter, and U_d is the DC bus voltage. Similarly, the output voltage of b-phase and c-phase can be easily obtained respectively as U_{bm} and U_{cm}. Suppose that all the switching tubes have desirable characteristics, the line voltage could be deduced as follows:

$$\begin{bmatrix} U_{ab} \\ U_{bc} \\ U_{ca} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} U_{am} \\ U_{bm} \\ U_{cm} \end{bmatrix} \tag{3}$$

The expression of phase voltage could be further derived:

$$\begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} U_{ab} \\ U_{bc} \\ U_{ca} \end{bmatrix} \tag{4}$$

Wherein, U_{an}, U_{bn} and U_{cn} are respectively the phase voltage of the three-phase load.

3.2. The PMSM Motor Model

The model of the PMSM motor is established according to the d-q coordinate transformation theory. The voltage equation is firstly built:

$$\begin{cases} v_d = Ri_d + L_d \dfrac{di_d}{dt} - P\omega_m L_q i_q \\ v_q = Ri_q + L_q \dfrac{di_q}{dt} + P\omega_m \left(L_d i_d + \psi \right) \end{cases} \tag{5}$$

Wherein, v_d and v_q are the input voltage (V) of PMSM d-q axes respectively, i_d and i_q are the current (A) of PMSM d-q axes respectively, R is the phase resistance (Ω), P is the number of pole-pairs of the motor, ω_m is the mechanical angular velocity of the rotor, ψ is a permanent magnet flux, L_d is the d-axis inductance and L_q is the q- axis inductance.

Through rearranging equation (5), we can obtain:

$$\frac{di_d}{dt} = \frac{v_d - Ri_d + P\omega_m L_q i_q}{L_d} \tag{6}$$

$$\frac{di_q}{dt} = \frac{v_q - Ri_q - P\omega_m \left(L_d i_d + \psi \right)}{L_q} \tag{7}$$

Through discretizing above equations, the iteration expression of the d-q current can be obtained as follows (T is the discrete period):

$$\begin{cases} i_d \left(n+1 \right) = i_d \left(n \right) + T \dfrac{di_d}{dt} \\ i_q \left(n+1 \right) = i_q \left(n \right) + T \dfrac{di_q}{dt} \end{cases} \tag{8}$$

The electromagnetic torque equation of the motor is:

$$T_e = \frac{3}{2} P \left[\psi i_q + \left(L_d - L_q \right) i_d i_q \right] \tag{9}$$

Wherein, T_e is the electromagnetic torque of the permanent magnet motor (Nm).

In the practical application of the HIL system, it is often required to simulate the motor of a variety of different vehicles. Of these motors, the range of rotational speeds (for instance, the maximum rotational speed of the In-Wheel-Drive motor is usually no more than 2,000 rpm, while the maximum rotational speed of the centralized driving motor with reducers may exceed 10,000 rpm), the power level, the DC bus voltage and other parameters vary a lot. However, in fixed-point calculation on the platform of FPGA, the range and precision of the data type are fixed, which requires the establishment of a normalized model that could uniformly measure the current, voltage and other parameters of different motors to avoid data overflow and meanwhile to ensure that different motors could all achieve sufficient accuracy in the simulation.

The physical quantities normalized by the following equations:

$$\begin{aligned} &R_n = \frac{R}{R_b}(p.u.), \quad L_{dn} = \frac{L_d}{L_b}(p.u.), \quad L_{qn} = \frac{L_q}{L_b}(p.u.), \quad \omega_{mn} = \frac{\omega_m}{\omega_b}(p.u.), \\ &i_{dn} = \frac{i_d}{i_b}(p.u.), \quad i_{qn} = \frac{i_q}{i_b}(p.u.), \quad v_{dn} = \frac{v_d}{v_b}(p.u.), \quad v_{qn} = \frac{v_q}{v_b}(p.u.) \end{aligned} \tag{10}$$

Wherein, R_b, L_b, ω_b, i_b and v_b are the reference values respectively of the resistance, the inductance, the rotational speed, the current and the voltage, and $R_n, L_{dn}, L_{qn}, \omega_{mn}, i_{dn}, i_{qn}, v_{dn}, v_{qn}$ are the normalized values of corresponding physical quantities respectively.

Substitute equation (10) into equation (5) to get the voltage equation, the current iterative equation and the normalized form of the torque equation. It is beyond the scope of this paper, so we will not go into details here.

In traditional PMSM models, the d-q axis inductance is set to a constant, but among a number of parameters of PMSM, inductance is highly non-linear, and its nonlinear change is the key to the actual performance of the motor [5]. Therefore, in order to improve the simulation accuracy of the HIL system, the nonlinear change of the inductance must be taken into consideration. In this system, the parameters of the permanent magnet motor inductance and the flux are generated by the finite element model created by the software JMAG (Specific methods of operation see 3.3.), which could well reflect the non-linear changes of the inductance, making the HIL simulation closer to the practical situation, so as to significantly improve the simulation accuracy of the motor.

3.3. The JMAG-Based PMSM Model

JMAG is used to establish the FEA model of the PMSM which is then input into LabView RT. The steps are as follows:

(1). Establish the aggregation model of the target PMSM in JMAG, set materials, winding forms, boundary conditions, *etc.*, and generate the mesh.

(2).Carry out simulation analysis to the PMSM finite element model established to generate the RTT file which contains the motor inductance parameters and the flux parameters.

(3).Compare the no-load back electromotive force curve of the JMAG motor model with that of the actual target motor to verify the correctness of the JMAG motor FEA model.

(4). In LabView RT, the inductance and flux parameters in RTT files generated by JMAG are retrieved in real time through calling the Read PMSM RTT File sub vi, which are input into the motor model for the high-precision real-time simulation.

The PMSM model used in this paper is built in accordance with the structure of an interior permanent magnet synchronous motor (IPM). Detailed parameters are shown in Table 1.

Table 1. Parameters of the PMSM

Parameter	**Value**	**Parameter**	**Value**
Number of pole-pairs	4	Slot space-factor	70.6%
Number of slots	48	Inner diameter of rotor	60mm
Rated power	50kw	Max. power	150kw
Rated torque	200Nm	Max. torque	750Nm
Rated rotational speed	2,400rpm	Max. rotational speed	7,200rpm

Stator phase resistance	0.3Ω	Cooling-down method	Water cooling
Turns of winding	22	Coolant flow	12L/min

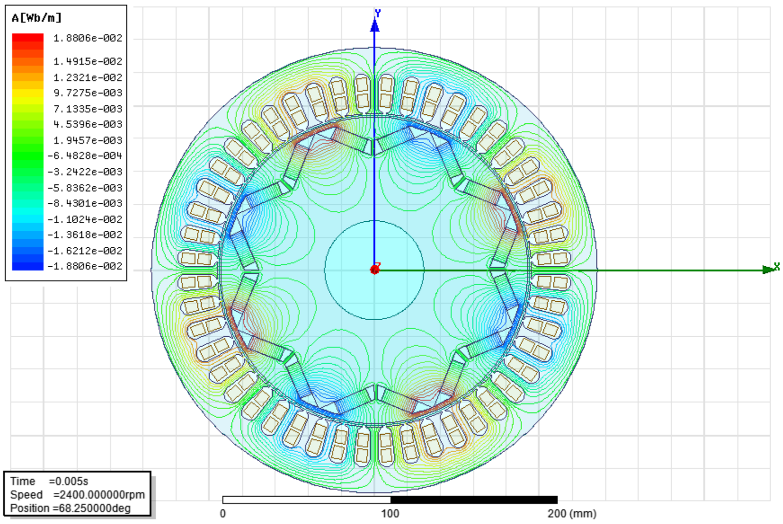

Figure 3. Flux Distribution Cloud Chart of the Motor

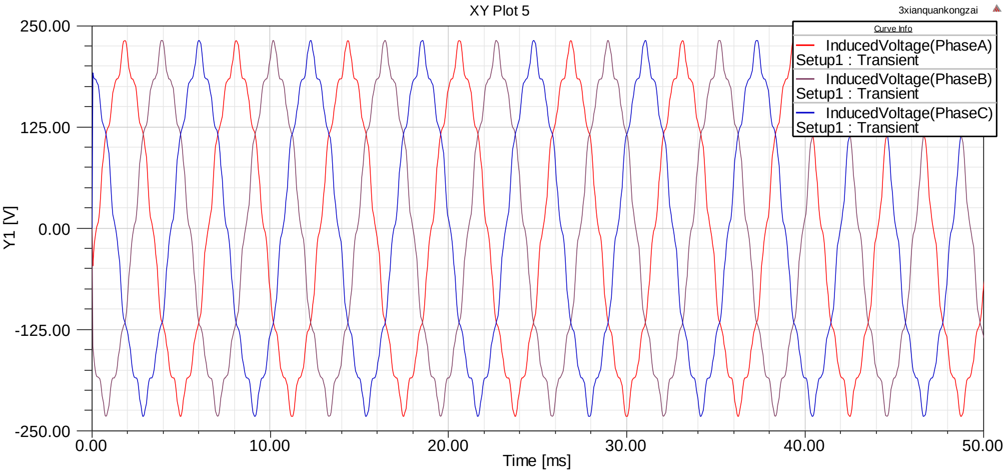

Figure 4. No-load Back Electromotive Force at 2400rpm

Figure 3 is the static magnetic flux distribution cloud chart of the PMSM finite element model built in this paper, from which it could be seen that its distribution of static magnetic field tends basically towards saturation. This is consistent with the actual situation of the PMSM motor. Figure 4 shows the simulation curve of the no-load back electromotive force of the finite element model constructed in this paper at the rotational speed of 2400rpm, with the peak value of 224.5V, while the peak value of the back electromotive force at 2400rpm obtained from the prototype test is 225.5V. The error is 0.4%, which verifies the correctness of the FEA model built in this paper.

3.4. The Kinematic Model of the Vehicle

The kinematic model of the vehicle is built in software CarSim RT. This software could generate a parametric model of the vehicle quickly and co-simulate with other real-time systems. Specific parameter settings of the vehicle are shown in Table 2.

Table 2. Parameter of Vehicle Model

Form of drive	Rear-wheel drive
Curb weight (kg)	1,300
Wheel base (mm)	2,700
Distance from the Centroid to the centre of the front axle (mm)	1,350
Height of Centroid (mm)	375
Wheel radius (m)	0.29
Form of suspension	Independent suspension
Tire specifications	235/45 R17
Reducer speed ratio	3.1

4. Data Acquisition and Interaction of the HIL System

Section two has already described the structure of the HIL system. The kinematic model of the vehicle, the driving motor system model and the vector control strategies (SVPWM) run separately on the three platforms including the DSP microcontroller, the FPGA platform and the PXI master controller. Therefore, the data interaction methods between different platforms need to be designed. Figure 5 shows the data exchange architecture of the EV’s system.

The kinematic model of the vehicle that operated by CarSim in the PXI Controller outputs the rotational speed signal of the output axis and the rotational position signal of the PMSM system to the FlexRIO FPGA board in real time situation [6]. The FPGA platform simulates the working state of the motor’s driving system and delivers the values of the electromagnetic torque of the PMSM to the PXI Controller to resolve the motion state of the vehicle. The data exchange between the PXI Controller and the FlexRIO FPGA is achieved via the DMA (Direct Memory Access). DMA technology is different in that it doesn’t need the participation of the CPU during data transmission, hence, greatly improving the data transmission speed. Synchronous data transmission with the FPGA could also be achieved.

The under-test controller needs to be connected respectively with the PXI system and the FPGA platform. It exchanges information with the PXI Controller via the CAN bus. The baud rate is set to be 500k to simulate the communication between the controller and the sensor and to get the motion state of the vehicle. The resolver input port of the controller and the input port of the current sensor are connected respectively with an FPGA Adaptor. FPGA RIO simulates the signals of the motor resolver and the current sensor, and outputs them to the controller in the form of simulating signals through the adapter. After processing, the controller will perform the SVPWM algorithm to generate the PWM driving signals of IGBT Gates which will be delivered to FPGA RIO in the form of digital signals.

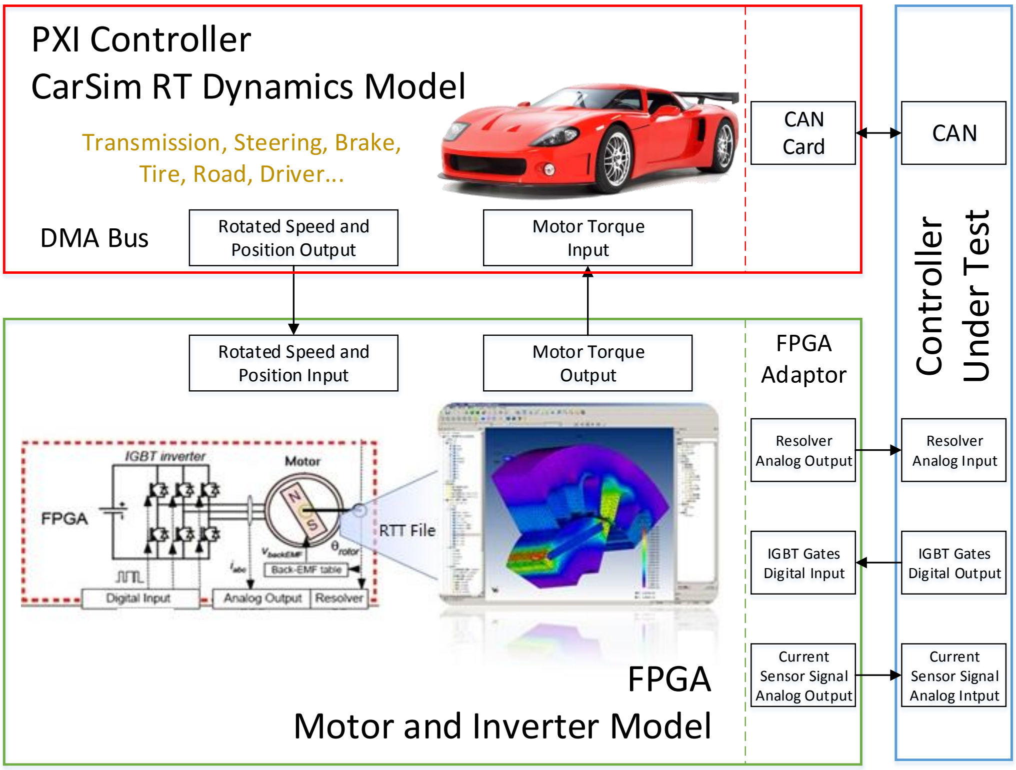

Figure 5. Data Interaction Structure of the HIL System

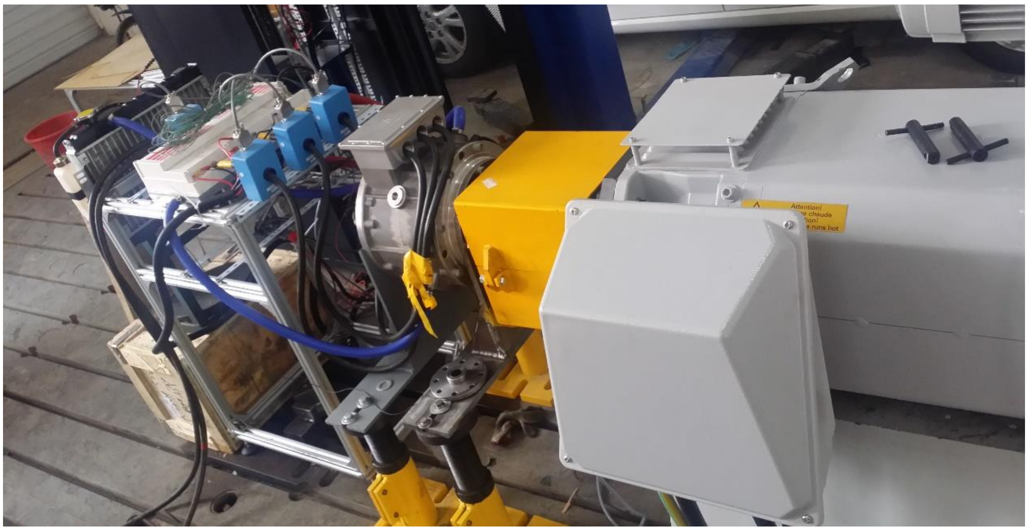

Figure 6. Motor Test Bench

5. Experimental Verification and Results Analysis

To verify the effectiveness of the motor model in the HIL simulation system, comparative experiments are carried out in the motor test bench as shown in Figure 6. This test bench is made up of dynamometer machines, torque sensors, current sensors, power analyzers and upper computers. The PMSM structure used in the comparative experiments is basically consistent with the FEA model. To facilitate the comparative analysis, the control method of $i_d = 0$ is taken in both the HIL test and the bench test as the control strategy of PMSM. The switching frequency of the inverter is 10 kHz and the dead-time compensation algorithm is added in bench test. The experiments are done mainly at a speed lower than the reference speed.

5.1. Comparison between the HIL and the Bench Test Results

The comparative experiment is carried out in a stable working state when the load torque $T_{Load} = 50 Nm$ and the rotational speed is 1000 rpm . The comparison between the results of the HIL platform and the bench test are shown in Figures 7-8.

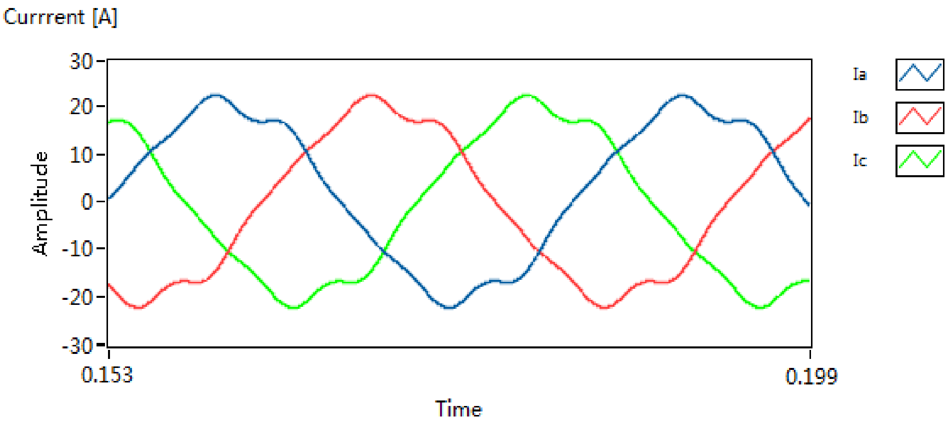

Figure 7. The Three-phase Current Curve of the HIL Simulation Test

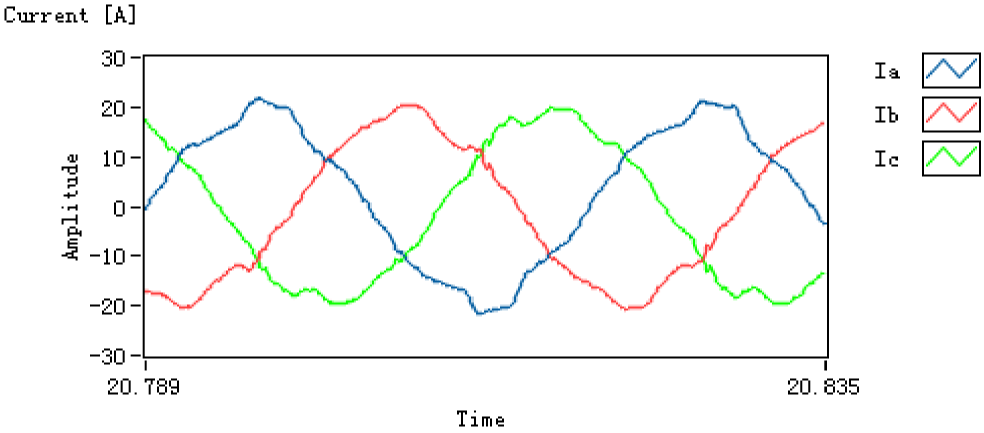

Figure 8. The Three-Phase Current Curve of the Bench Test

Figure 7 shows the three-phase current curve of HIL simulation in steady-state conditions and Figure 8 shows the three-phase current curve of bench test in the same condition. It could be seen from the comparison of the curves that the HIL simulation test basically reverts to the working state when the vehicle actually runs. The simulation step size of the HIL system reaches 1μsec, which is sufficient to meet the simulation needs of the motor's controller.

5.2. Results and Analysis of the Vehicle HIL Test Based on the Driving System Model of the Motor

The vehicle HIL test system is verified in the working state of 0-60 rapid acceleration with TCS control. TCS is implemented in the method of self-adaptive PID control. Through the TCS controller, the driving system of the motor is controlled, and the control over the traction is realized by adjusting the driving torque. The results are shown in Figures 9-11.

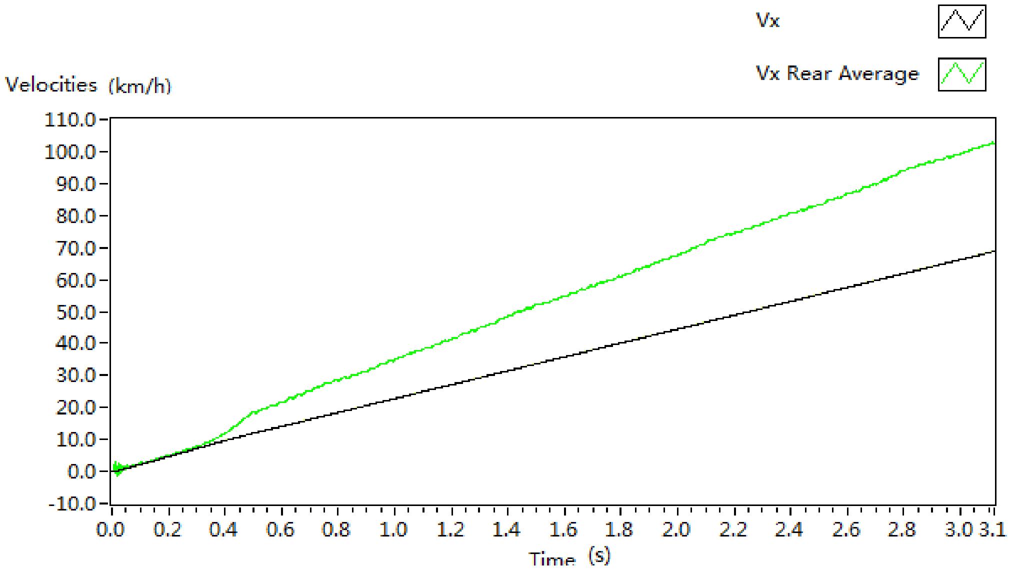

Figure 9. Curves of Vehicle Speed and Rear Wheel Speed

It could be seen from the simulation results that the control via TCS successfully adjusts the driving torque that is output to the kinetic model of the vehicle from the model of the PMSM system. The driving tire slip ratio of the vehicle at the time of rapid acceleration is controlled to be around 0.3 to avoid the loss of power or out of control due to the slippage of the tire. It could be seen from the driving torque curve shown in Figure 11 that the motor model of the HIL system could reflect the torque fluctuations in the actual operation of the motor. Such a motor model is closer to the real situation compared with the ideal power-sourced motor model and the traditional fixed value motor model. Such kind of torque fluctuations should be taken into account in the development of kinetic control, as the torque fluctuations may have a significant impact on the control quality.

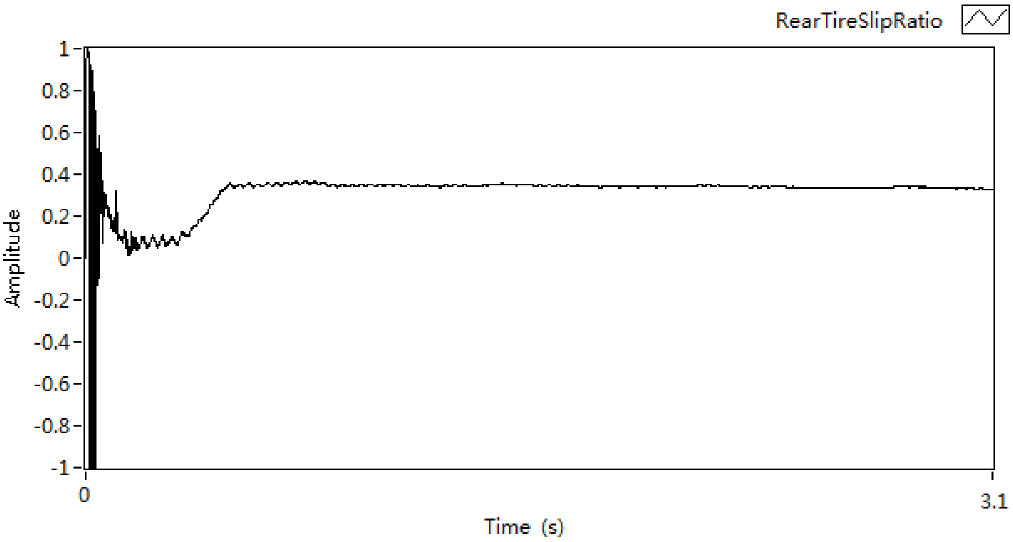

Figure 10. Curve of Slip Ratio

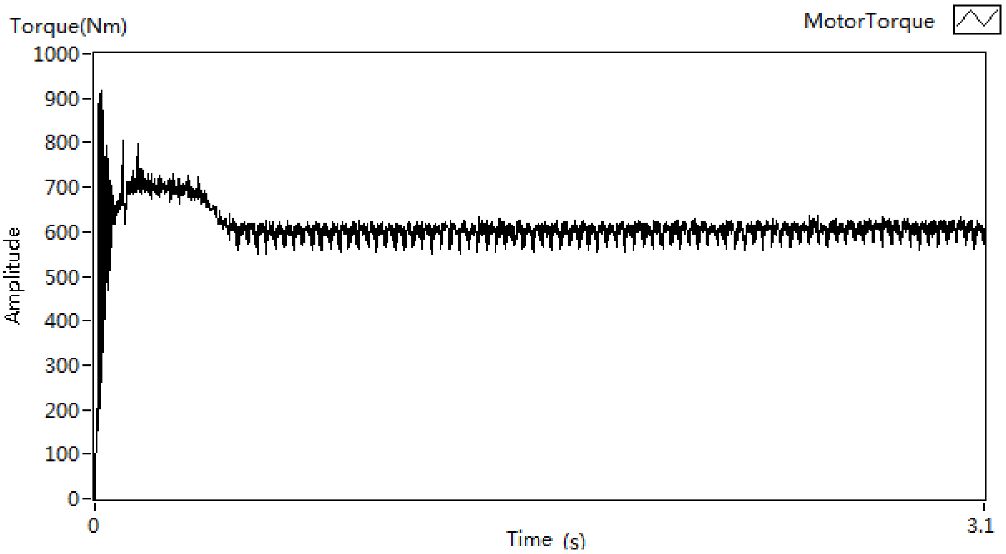

Figure 11. Driving Torque Curve

6. Conclusion

In this paper, a finite element model is built in the software JMAG, on the basis of which, a PMSM real-time simulation and testing system is constructed on the platform of FPGA. Through connecting with the kinetic model of the vehicle, a complete EV HIL system is formed and the simulation step size reaches 1μsec. The PMSM real-time simulation system established in this paper solves the problems in nonlinear parametric modeling on the platform of FPGA. And the PMSM model can well revert to the actual working state of the motor driving system through comparing with the results of the bench test.

The simulation results of the vehicle HIL system proves that the motor driving system model could work coordinately with the vehicle kinetic model, which is of great significance to the development of the controller of EVs, the development of the powertrain, the testing of dynamic control, *etc.* This HIL system could shorten the development cycle of EV mechatronic projects and save development costs.

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