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# Research Article

# **On-Load Electromagnetic Compatibility Test and Simulation Closed-Loop of the Electric Drive System of New Energy Vehicles**

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Received 29 July 2022; Revised 12 August 2022; Accepted 23 August 2022; Published 7 September 2022

Academic Editor: Nagamalai Vasimalai

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In order to solve the problem of high-amplitude and high-frequency interference generated by the electric drive system of new energy vehicles, the author proposes a closed-loop research method for on-load electromagnetic compatibility testing and simulation for electric drive systems of new energy vehicles. The method includes EMC design of the electric drive system on-load test equipment, establishment of a conducted EMI simulation platform for the electric drive system under load conditions, and optimization of the conducted EMI performance of the electric drive system based on key parameters and PWM control. Experimental results show that if the parasitic inductance of the IGBT gate increases, the conducted emission level in the frequency range of  $2\sim30$  MHz will increase, and there is basically no change at the low frequency, and the position of each resonance point shifts to the relatively low frequency. The experiment was replaced with the DPWM3 modulation mode, and the conducted emission amplitude was reduced by about  $2 \, dB\mu V$  in the range of  $200 \, kHz \sim 2 \, MHz$ , and there was basically no change on the whole. *Conclusion*. It is proved that the electromagnetic compatibility closed-loop development technology of the electric drive system of new energy vehicles under load conditions can meet the development needs of new energy vehicles in the environment where energy problems and air pollution problems are becoming more and more serious.

### 1. Introduction

With the increasingly prominent problems of energy and air pollution, the research and development of new energy vehicles has great practical significance. Vigorously developing new energy vehicles is the only way for my country to transform from a big automobile country to a powerful automobile country, and at the same time, it is also an important measure to deal with climate problems and promote green and low-carbon development [1]. Highly autonomous vehicles realize commercial applications in limited areas and specific scenarios. New energy vehicles have added many power electronic devices, and the electric drive system as the main power source has the characteristics of high power, high voltage, high current, and high switching frequency, as shown in Figure 1. These devices will cause electromagnetic interference to other electrical systems and equipment during operation, the electromagnetic compatibility problem of new energy vehicles is becoming more and

more serious, which greatly limits the development of new energy vehicles [2]. Automotive electromagnetic compatibility refers to the ability of the entire vehicle and its components to work normally in the electromagnetic environment in which it is located, without causing undesired electromagnetic interference to other things in the environment. In order to ensure the reliability, safety, and stability of the car, it is required that the on-board electronic equipment can work normally under the interference of other power electronic equipment; it will not affect the safe and stable operation of other electronic equipment, that is, achieve electromagnetic compatibility [3]. In this big environment, the on-load electromagnetic compatibility test and simulation closed-loop research of the electric drive system of new energy vehicles, aiming at the main problems existing in the electric drive EMC on-load test system, the mechanism is analyzed, and the solutions and measures are proposed, which provide reliable, standard-compliant, and cost-effective solutions for new energy OEMs; component



FIGURE 1: New energy vehicle electric drive system.

manufacturers and third-party testing agencies in the field of electric drive EMC on-load evaluation break the technical monopoly of the electric drive EMC on-load test system and improve China's research and development capabilities and voice in the field of automotive electronics EMC [4].

#### 2. Literature Review

The electromagnetic compatibility of the battery system of new energy high-voltage pipe fittings is studied; in terms of common mode noise suppression, Mott and Priefer analyzed the common mode and differential mode interference in the electric vehicle drive system through experiments and proposed that the multilayer printed circuit board technology should be adopted for the differential mode interference [5]. Ajay and Jaya proposed in the literature that when the AC motor and the PWM inverter are connected by a long cable and when the transmission time of the PWM pulse in the cable exceeds 1/3 of the rise time of the PWM pulse, a total reflection will be sent at the motor end. It is verified that increasing the rise time of the PWM pulse can greatly reduce dv/dt at the motor end, thereby reducing the generation of electromagnetic interference [6]. Xie and Yuan believed that the common mode current was mainly caused by high frequency switching, used the equivalent circuit method to analyze the generation mechanism of common mode noise, and proposed a new type of a BOOST balanced switch converter [7]. This kind of a converter is active and can generate a current with the same magnitude and opposite phase as the common mode current, and in theory, it can completely suppress the generation of common mode interference. Based on a certain type of hybrid vehicle, Welti analyzed the electromagnetic environment in the vehicle and the coupling interference mechanism to the battery

management system and studied the anti-interference technology of the battery management system, focusing on improving the anti-interference ability of the battery management system, in order to realize the electromagnetic compatibility design of the battery management system [8]. Wang et al. carried out the theoretical research on the electromagnetic compatibility of the battery management system, the power line conduction of the battery management system, the modeling and simulation of the radiation interference, and the electromagnetic compatibility test analysis of the battery management system [9]. Antonov et al. determined the main interference sources and coupling paths of the high-voltage system, analyzed the influence of the interference sources generated by the motor controller and the internal switching devices of the DC/DC converter on the electromagnetic compatibility performance of the power battery, and established the power equivalent model of battery coupled interference and applied the extracted interference sources to the coupled interference model [10]. Based on the electromagnetic shielding theory and the finite element method, Dogra et al. combined numerical simulation and the Robinson equivalent model method, and the factors affecting the shielding effectiveness of the open rectangular cavity were studied [11]. The electromagnetic compatibility analysis of the battery management system has improved the electromagnetic compatibility characteristics of the battery management system to varying degrees, which has a great reference effect. On the basis of the current research, the author proposes an electromagnetic compatibility closed-loop development technology for the electric drive system of new energy vehicles under load conditions, which mainly includes three key links: the test platform focuses on the formulation and improvement of test standards and test methods and is a means to directly evaluate the electromagnetic compatibility performance of the electric drive system; the test equipment is centered on the development of a standardized and low-cost test bench, which is the hardware support for the electromagnetic compatibility test of the electric drive system; the simulation platform focuses on the parameter design, prediction, and optimization of forward development, which is a means of controlling the EMC performance of electric drive system products in the early stage of design [12].

#### 3. Methods

#### 3.1. EMC Design of On-Load Test Equipment for the Electric Drive System

3.1.1. 3D Electromagnetic Modeling of On-Load Test Equipment for the Electric Drive System. According to the geometric model, block simplification processing, material property assignment, mesh division, and other operations are carried out, and a three-dimensional electromagnetic model of the electric drive system under load test equipment is established [13]. It mainly includes the end of the dynamometer motor, the shaft through the wall and its connecting parts, the parts of the end under test, and the dark room.

3.1.2. Shaft Current Simulation Analysis. In order to simulate the shaft current path generated by the dynamometer motor, the excitation of the current source is set on the axial surface of the output shaft of the dynamometer motor with an amplitude of 1A, and the direction is along one side of the anechoic chamber [14]. Set up three axial current simulation observation points, which are located at the shaft head of the shaft through the wall outside the semianechoic chamber (observation point A), the shaft head of the shaft through the wall inside the anechoic chamber (observation point B), and the position of the test piece installed inside the anechoic chamber (observation point C). The effects of different materials on the shaft current are compared and analyzed, the values of the three materials at the same observation point are compared, and the results are shown in Figures 2(a) and 2(b).

3.1.3. Shielding Effectiveness Simulation Analysis. Considering the electromagnetic field in space, current and plane wave excitations need to be applied in the excitation setup [15]. The shape of the hole through the wall is set as a circle, and the apertures of the openings in the shielding wall are 370 mm, 380 mm, 390 mm, and 400 mm, respectively. The shielding effectiveness test is carried out under these four sizes, and the results are shown in Figure 3.

From this, it can be seen that in the 9 kHz~2 MHz and 30~200 MHz frequency bands, the shielding effectiveness is generally better when the diameter of the hole through the wall is 390 mm; in the range of 2~30 MHz, there is not much difference between the diameter of 390 mm and 400 mm through the wall; in the two frequency bands of 141~157 MHz and 190~197 MHz, the shielding effectiveness is relatively good when the diameter of the through-wall hole

is 380 mm [16]. In order to protect the integrity of shielding, when designing the shielding cover, the through-wall shaft should be completely surrounded, and the electromagnetic interference in the space should not enter the semianechoic chamber as much as possible. The shaft current is suppressed by grounding, so a conductive grounding ring is installed outside the dark room of the on-load test system, on the outside of coupling, and at one end of the shaft through the wall [17].

The simulation test was carried out with the shielding cover alone, and compared with the simulation results without the shielding cover, it can be seen that after the shielding cover is installed, the overall shielding efficiency is improved; especially in the frequency bands of 9 kHz~5 MHz, 7~50 MHz, and 60~200 MHz, the shielding effectiveness is significantly improved by 14~40 dB. After the shielding case is installed, the shielding effectiveness around 6 MHz becomes poor, and further research is needed. In general, installing a shielding case is one of the effective measures to improve the shielding effectiveness [18]. After adding the shielding cover, continue to install the conductive grounding ring for the simulation test and compare the shielding effectiveness simulation test results of no shielding cover, only the shielding cover, and the conductive grounding ring; after installing the conductive grounding ring, the shielding effectiveness is improved again; at frequencies below 2 MHz, the shielding effectiveness is increased by at least 6 dB compared to the case where only the shield is installed, and the shielding effectiveness in frequency bands of 7~10 MHz, 25~30 MHz, and 50~80 MHz is significantly improved by 3~10 dB. It can be seen that the installation of the conductive grounding ring can effectively reduce the electromagnetic interference caused by the shaft current.

3.1.4. EMC Performance Evaluation of Electric Drive System On-Load Test Equipment. Using the iterative optimization of the above parameters and filter design, a set of on-load test equipment "MotorChamber" for the through-wall electric drive system that meets the standard requirements is developed, and the electrical performance specifications are shown in Table 1.

Under the working conditions of a dynamometer speed of 7000r/min and a current of 150A, the radiation emission test in the dark room was carried out to evaluate the EMC performance of the loaded test equipment [19]. The radiation emission test results of each frequency band are compared with the level 5 limit of GB/T18655-2018; the results show that the radiation emission in the darkroom is lower than the level 5 limit of GB/T18655-2018 by more than 20 dB in all frequency bands, which meets the requirements [20].

#### 3.2. Establishment of Simulation Platform for Conducted EMI under Load Conditions of the Electric Drive System

3.2.1. Conducted EMI Model Structure of the Electric Drive System. According to the actual circuit structure of the



FIGURE 2: Comparison of simulation results of through-wall shafts using different materials. (a) Data comparison of the observation point B. (b) Data comparison of the observation point C.



FIGURE 3: Comparison of simulation results of through-wall holes with different diameters.

TABLE 1: Test system electrical specifications.

Category	Parameter
High voltage supply voltage/V	1000
Low voltage supply voltage/V	9~200
Rated current/A	500
Stand power/kW	220
maximum speed/(r/min)	7000
highest torque/(N·m)	1000

integrated electric drive system, combined with the layout of the test standard, the time domain simulation results are converted by the established mathematical model of the EMI receiver to obtain the peak and average spectrum. (2) The motor load model of the electric drive system establishes the electromagnetic torque equation of the onboard permanent magnet synchronous motor as shown in the following equation:

$$T_{em} = p(\varphi_d i_q - \varphi_q i_d) = p[L_{md} i_f i_q + (L_d - L_q)i_d i_q]$$
  
=  $p[\varphi_f i_q + (L_d - L_q)i_d i_q].$  (1)

Among them,  $T_{em}$  is the electromagnetic torque, p is the number of motor pole pairs,  $\varphi_d$  is the flux linkage,  $i_d$  is the direct axis current,  $i_q$  is the quadrature axis current,  $L_d$  is the direct axis inductance, and  $L_q$  is the quadrature axis inductance.

In order to obtain the values of the above parameters of the motor under various working conditions, a three-dimensional electromagnetic simulation is carried out; according to the main design parameters of the motor, a three-dimensional electromagnetic model of the motor is established, and the boundary conditions are set for simulation, and the characteristic parameter curves of the motor are output. The motor needs to use the maximum torque/ current control, in order to find the load characteristic parameters corresponding to the maximum torque under each working condition and establish the motor load model under each working condition. Taking the motor torque of 3000r/min and the current of 100N·m as an example, the speed and torque of the load model are shown in Figures 4(a) and 4(b).

3.2.2. Conducted EMI Model Verification of the Electric Drive System. The conducted EMI model of the electric drive system is established, where the circuit simulation step size is 2 ns, and the backward Euler solver is used to solve it. Set the intermediate frequency bandwidth (RBW) and step size of the EMI receiver according to GB/T18655-2018. The RBW in the 150 kHz~30 MHz frequency band is 9 kHz, and the step size is 4 kHz.



FIGURE 4: The effect of speed and torque realization of the loaded model. (a) Speed realization effect and (b) torque realization effect.

#### 4. Results and Discussion

4.1. Validation Results of the Conducted EMI Model of the Electric Drive System. Under the working conditions of motor torque of 3000r/min and current of 50N·m, the high-voltage LISN positive and negative conduction emission (voltage method) simulation is carried out, and the comparison results with the test spectrum are shown in Figure 5.

It can be seen that in the high frequency range of 150 kHz~20 MHz, the high-risk resonance points concerned in conducted emission are basically consistent, the amplitude error of the main resonance point is less than  $6 \text{ dB}\mu\text{V}$ , and the spectrum trend in the overall range is consistent.

4.2. Optimization of Conducted EMI Performance by the PWM Control Method. In engineering, the electric drive system generally adopts the SVPWM (space voltage vector pulse width modulation) method. Change the PWM (pulse width modulation) mode to DPWM (discontinuous pulse width modulation) and analyze its influence on the electromagnetic interference of the system. Change the modulation mode to DPWM3 for the simulation test and compare it with the simulation result of the SVPWM modulation. It can be seen from the results that by replacing the DPWM3 modulation method, in the range of 200 kHz~2 MHz, the conducted emission amplitude is reduced by about 2 dB $\mu$ V, and there is basically no change on the whole. Then, change the modulation mode to DPWMmin for the simulation test and compare it with the simulation results of the SVPWM method. It can be seen from this that the overall conducted emission level is reduced by replacing the modulation mode with DPWMmin, the amplitude at the 4 MHz resonance point is unchanged, and the amplitude at the 8 MHz resonance point is reduced by about  $8 \, dB \mu V$ .



FIGURE 5: 150 kHz~30 MHz conducted emission simulation and test comparison.

#### **5.** Conclusion

The author proposes a closed-loop research method for onload electromagnetic compatibility testing and simulation for electric drive systems of new energy vehicles. The method includes EMC design of the electric drive system on-load test equipment, establishment of a conducted EMI simulation platform for the electric drive system under load conditions, and optimization of the conducted EMI performance of the electric drive system based on key parameters and PWM control. The following conditions were observed through experiments: simulation platform based on electric drive system; IGBT gate parasitic inductor with motor torque 3000R per minute and current 100N·m under typical working conditions; the effect of IGBT and the parasitic capacitance of the heat sink on the conduction interference; effect of replacing PWM (pulse width modulation) mode with DPWM (discontinuous pulse width modulation) on system electromagnetic interference. The specific embodiment is that if the parasitic inductance of the IGBT gate increases, the conducted emission level in the frequency range of 2~30 MHz will increase; there is basically no change at the low frequency, and the position of each resonance point shifts to the relatively low frequency. The experiment was replaced with the DPWM3 modulation mode, the conducted emission amplitude was reduced by about 2 dB $\mu$ V in the range of 200 kHz~2 MHz, and there was basically no change on the whole.

#### **Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

## **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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