Research on EMC Simulation Method of Conducted Emissions Current Probe Method for Electric Vehicle Battery Pack

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Abstract. The electric vehicle generates more serious electromagnetic interference than the traditional cars. As one of the core components, the battery pack affect the vehicle’s electronic equipment seriously and it is susceptible to interference from high-voltage components Simultaneously. This chapter mainly studies the conducted emissions of battery packs. By establishing of the equivalent circuit model of the conducted emissions current probe method for the battery pack, and analysing according to the test conditions, and finally comparing with the test results to verify the accuracy and effectiveness of the method.

Keywords: battery pack, conducted emissions, current probe method, simulation.

1. Introduction

Electric vehicles directly utilize the electric drive system as the power source, equipped On-Board Charger, DC/DC converters and other components, and most use high-power semiconductor switching devices. Strong electromagnetic interference will be generated, due to the high-voltage and high-current transients in the switching process of high-power semiconductor switching devices. More high and low-voltage wiring harnesses inside the vehicle, which are widely distributed, and the intelligent and entertainment equipment in the vehicle gradually increase, which causes the electromagnetic environment in the vehicle more complicated. The electromagnetic compatibility problem affects the normal operation of electronic equipment, it causes the failure of the control system and the interruption of communication, which lead to serious hidden dangers to driving safety [1,2]. On the one hand, the battery pack is directly connected to the motor controller to supply power to the three-phase AC drive motor, on the other hand, it is connected to the DC/DC converter to supply power to the low-voltage load. The electromagnetic interference resulted by its normal operation interferes with other sensitive equipment through cable conduction or spatial coupling [3]. The electromagnetic compatibility problem of battery packs is an important link in the quality system of automobile manufacturing, and it is also an unavoidable research and development focus.

In recent years, domestic and foreign countries have begun to pay more attention to the issue of electromagnetic compatibility in electric vehicles. Many automobile companies and scientific research
institutions have begun to study electromagnetic compatibility issues of electric vehicles. For example, in 2009, Jilin University studied the crosstalk problem of automotive wiring harnesses based on the transmission line theory, analyzed the shielding effectiveness of the vehicle body based on the slot antenna theory, and analyzed the interference source in the vehicle based on the wavelet packet decomposition technology [4]. In 2010, Chongqing University conducted research on the conduction interference of ignition system, wiper system, DC/DC converter and electric drive system based on the method of field-circuit combination [5,6]. In 2014, Chongqing University analyzed the impact of DC/DC converters, DC/AC converters and other interference sources with the battery pack as the conduction path [3]. Currently, the research on electromagnetic compatibility of electric vehicles is mainly for electric drive systems, and for the performance design of the battery management system, module thermal analysis and life analysis, battery cell safety performance, etc.

Aiming at the above problems, this paper takes the battery pack as the main object, establishes a three-dimensional model of the battery pack, including shielding shell, high-voltage busbar, low-voltage wiring harness, etc.; then builds a simulation model based on the test platform. Finally, the simulation and actual measurement results are compared to verify the effectiveness of the method. Certainly, the model of electric drive system and battery pack can be integrated to further study the electromagnetic compatibility simulation problem of the whole vehicle.

2. Analysis of conduction coupling theory

2.1. Circuit coupling
Circuit conduction interference coupling is the most common conduction coupling method, in which there are at least two mutually coupled circuits. Circuit conduction interference mainly depends on the current and voltage of the connecting line. This type of coupling usually occurs in the ground and (or) power system. Circuit coupling is illustrated in Fig. 1.

![Circuit Coupling](image)

(a) Two circuit common ground

(b) Two circuits share one power system

Fig 1. Schematic diagram of circuit coupling.

2.2. Electric field coupling
A simple representation of the electric field (capacitive) coupling between two wires is shown in Fig.2. The interference source $V_1$ of the first conductor is coupled to the second conductor through the parasitic capacitance $C_{12}$ between the two conductors. In the Fig.2 capacitance $C_{1G}$ is the ground capacitance of
the first conductor, and capacitance $C_{2G}$ is the ground capacitance of the second conductor. The resistance $R$ is caused by the circuit connected to the second conductor.

![Diagram](a) Two circuit common ground

![Diagram](b) Two circuits share one power system

**Fig 2.** Schematic diagram of electric field coupling

The coupling voltage $V_2$ is proportional to the amplitude of the interference source, the frequency of the interference source, the ground resistance $R$ of the circuit, and the mutual capacitance $C_{12}$ between the two conductors.

2.3. *Magnetic field coupling*

A simple representation of the magnetic (inductive) coupling between two circuits is shown in Fig. 3(a). The current $I_1$ in the interference circuit is coupled to the second circuit through the mutual inductance $M$ of the two circuits. Mutual inductance $M$ is the mutual inductance of two circuits, which is determined by the geometry of the two circuits and the magnetic characteristics of the medium between the two circuits. $V_2$ is the noise voltage induced on the coupled circuit. The equivalent circuit of the inductive coupling circuit is shown in Fig.3 (b).

![Diagram](a) Simple representation

![Diagram](b) magnetic field coupling equivalent

**Fig 3.** Schematic diagram of magnetic field coupling
The noise voltage $V_2$ is proportional to the self-inductance value (the rate of change of the current in the first circuit with respect to time) in the noise source circuit and the mutual inductance between the two circuits.

In practice, the electric field coupling and magnetic field coupling of two adjacent circuits or systems exist at the same time, and there are both electric field interaction and magnetic field interaction. The induced voltage generated by electric field coupling is connected in parallel in the interfered circuit and has nothing to do with the load of the interfered circuit; the induced voltage generated by magnetic field coupling is connected in series in the interfered circuit and is related to the load of the interfered circuit.

3. System simulation model

Before establishing the system simulation model of the battery pack conducted emissions current probe method, we need to establish the simulation model of each module, which mainly includes the following 4 aspects:

3.1. High-voltage cable and low-voltage cable model

First, create a battery pack model in the three-dimensional electromagnetic field full-wave simulation software, which mainly includes: the upper cover, the lower shell, the module box, the ground plane, and all cable model. Then utilize the transmission line solver to generate an equivalent model of the cables inside and outside the battery pack, as shown in Fig. 4. When solving, the transmission line method takes the spatial distance, skin effect and dielectric loss into account, which greatly improves the accuracy of the model. The specific solution process is described as:

- The software will automatically check the metal structure around the cable harness and mesh the cross section of each small section of the cable.
- Extract the transmission parameters (R, L, C) in each segment of the divided cable, and each segment will be transformed into an equivalent circuit of a transmission line.
- All the small segments will be connected into a complete circuit model which is equivalent to the entire cable model [9,10].

![Fig 4. Equivalent model of the cables inside and outside the battery pack](image)

3.2. Interference source model

Most mainstream electromagnetic simulation software provides various types of excitation sources, such as point sources, plane waves, Gaussian waves, current sources, voltage sources, pulses, etc. For ideal conditions, they can be directly used as needed [11]. For actual working conditions, Usually need to use the voltage/current waveform measured by the oscilloscope as the interference source.

In the process of obtaining the excitation source, to ensure that the frequency information is not lost, the frequency interval cannot be higher than twice the test. Simultaneously, in order to ensure that the spectral width of the time domain signal after Fourier transform can cover the frequency range of the test, the sampling rate of the oscilloscope should not be too low[12]. The time-domain signal of the cell voltage sampling signal line obtained by the current clamp is shown in Fig. 5.
3.3. Model equivalent circuit model

Lithium-ion cell is a chemical reaction system, presenting complex frequency-varying characteristics, it is difficult to use a simple lumped parameter model to be equivalent[13]. It is difficult to obtain the high-frequency parameters of lithium-ion cell in actual engineering. For this purpose, offline measurement is performed. The impedance characteristic diagram of lithium-ion cell is extracted by impedance analyzer as shown in Fig.6.

\[
 f(s) \approx \sum_{n=1}^{N} \frac{c_n}{s-a_n} + d + es \tag{1}
\]

Where \( c_n \) is a residue, \( a_n \) is a pole and they are both real numbers or conjugate complex number pairs, \( d \) and \( e \) are real numbers. The comparison between the 16-order fitting result and the measured result is shown in Fig. 7, it illustrates that the vector matching method is effective and the fitting order is sufficient. Generally, the lower the order, the worse the fitting accuracy. The higher the order, although the accuracy can be improved, it will also increase the circuit complexity, and too high order may seriously accumulate errors.
Fig 7. Comparison of measured and fitted results

According to the fitting result of the single cell and the series-parallel relationship, the equivalent circuit model of the module is shown in Fig. 8.

Fig 8. Equivalent circuit model of the module

3.4. High-voltage LISN and low-voltage LISN circuit models
The EMC standard test requires that the external low-voltage 12V power cord is connected to the low-voltage linear impedance stabilization network (Line Impedance Stabilization Network, LISN), and the external high-voltage power cable is connected to the high-voltage LISN. The main function of LISN is to isolate radio wave interference, provide stable test impedance, and filter [14]. The LISN model is shown in Fig. 9.
4. Result analysis
First, perform the test according to the standard cisp25-2016. The detailed layout is shown in Fig. 10(a). The test condition is 4.7A constant current discharge. Then measure the conducted disturbance values in the frequency range of 0.15MHz-245MHz. According to the test platform, the conducted disturbance current simulation circuit model created is shown in Fig. 10(b). Finally, the conducted disturbance values at 50mm and 750mm of the high-voltage and low-voltage wiring harness from the battery pack were obtained.
The comparison between the simulation results and the measured results is illustrated in Fig. 11. The red curve in the figure is the limit value of the conducted emissions current method, the green curve is the standard test result, and the blue curve is the simulation result. From the comparison results, the simulation results are in good agreement with the overall trends of the test results, and the average error does not exceed ±6dB.

(a) Comparison results of the high voltage part at a distance of 50mm from the battery pack

(b) Comparison results of the high voltage part at a distance of 750mm from the battery pack

Fig 10. Test layout and simulation model diagram of battery pack conducted emissions current method
5. Conclusion

In summary, the model established in the article can more accurately describe the frequency domain characteristics of the disturbance signal generated by the battery pack during normal operation. Establishing the equivalent model of the internal and external cables of the battery pack, the interference source model, the module equivalent circuit model, etc., the simulation of the conducted emissions current method of the battery pack is realized, and the simulation results are compared with the test results. Draw the following conclusions:

- In the frequency range of the conducted emissions current method, the simulation results are consistent with the overall trend of the measured results.
- The results of the comparison between simulation results and test results verify the accuracy of the conducted emissions current method model, and also prove the accuracy of the simulation method.
- The equivalent model of the battery pack cable established in the article can also be applied to the prediction of vehicle conducted emission.

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