Analysis and Optimization of Electromagnetic Compatibility for Electric Vehicles

Jian Hu, Xiao Xu, Dongdong Cao, and Guibin Liu

Abstract—Due to the changes of energy storage sources, driving systems, vehicle control units, etc., the electromagnetic compatibility (EMC) of electric vehicles is facing greater challenges than that of conventional oil-fueled vehicles. On the one hand, the use of high-power and high-voltage electrical components will generate high electromagnetic interference (EMI) energies in actual operation. On the other hand, automotive electronics with high integration and sensitivity is more susceptible to EMI, which is directly related to the safety of vehicles. In this paper, the EMI mechanism and suppression measures of motor driving systems, charging systems and other low-voltage systems are investigated. The results show that the main sources of EMI in electric vehicles are the quick switching of power switches, the operation of motor windings and the issue of signal coupling between high voltage cables and low voltage cables, and the EMI can be suppressed effectively by shielding, filtering and optimization of system principles.

Index Terms—Electric vehicles, Electromagnetic compatibility (EMC), Electromagnetic interference (EMI) mechanism, Suppression measures.

I. Introduction

Promoting the development of electric vehicle industry is of great significance for adjusting energy structure and reducing environmental pollution, which has attracted many countries' attention to the research on the electric vehicle technology. Compared with conventional oil-fueled vehicles, electric vehicles have great differences in energy storage sources, driving systems, vehicle control units and other aspects, which directly affect the performance of vehicles. Notably, the use of high-power and high-voltage electrical components (e.g. driving motors, high-voltage power batteries and power switches, etc.) is a prominent feature for electric vehicles. These devices will generate high EMI energies in actual operation, which will affect the surrounding environment as well as on-board electronic devices [1]. In addition, with the increasing demand of safety, intelligence and entertainment, the number of on-board electronic devices (e.g. electronic braking system, anti-lock braking system and navigator, etc.) is increasing. Due to the high integration and electromagnetic sensitivity of these devices or systems, as well as more complex electromagnetic environment of vehicles, automotive electronic devices usually unable to work properly [2]. Therefore, how to effectively solve the EMC problems and improve the safety and reliability of electric vehicles is an important issue that restricts the further development of electric vehicles. At present, many works have been done to solve the EMC problems of key systems and components of electric vehicles [3-10], which can provide guidance for optimizing the performance of individual products.

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In this paper, the exploration of common problems and overall optimization are taken into account for solving the EMC problems of electric vehicles, and the main research contents include: (a) investigating the characteristics of disturbance sources, (b) analyzing EMI coupling paths under different working conditions, (c) studying the optimization measures of electronic and electrical systems for restraining the influence of EMI on the surrounding environment or other electronic equipment, (d) carrying out experiments to verify the validity of optimization measures.

II. Analysis of Electromagnetic Interference Mechanism of Electric Vehicles

EMI mechanism of electric vehicles will be different under different working conditions or operating scenarios Therefore, it is necessary to discuss and analyze such problems as disturbance sources, EMI coupling paths and suppression measures in different scenarios.

A. Motor Driving System

1) Characteristics of Disturbance Sources

EMC problems of motor driving systems usually involve driving motors, motor controllers, inverters, high voltage cables, etc. Generally, when the motor driving system is in working state, the power switch in the inverter is controlled by a PWM signal and its working frequency can reach 2 KHz to 20 KHz [4] [11]. Due to the quick switching of power switch, the inverter will generate electrical interference signals with high transient voltage and large pulse current, which will become an important disturbance source in the motor driving system. In order to illustrate the EMI problem of the power switch, a spectrum analysis of high transient voltage was carried out in this study. As shown in Fig.1, the high transient voltage of the power switch is described as a periodic ideal trapezoidal pulse wave.

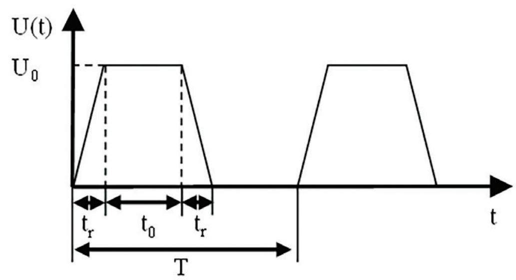


Fig. 1. The time domain waveform of the periodic ideal trapezoidal pulse wave

The Fourier series expansions of the periodic ideal trapezoidal pulse wave are given as:

$$U(t) = 2U_0\frac{\tau}{T} + \sum_{n=1}^{\infty} C_n \cos\left(\frac{2\pi n t}{T} + \varphi_n\right) \qquad (1)$$

$$C_n = 2U_0 \frac{\tau}{T} \frac{\sin\left(\frac{n\pi\tau}{T}\right)}{\left(\frac{n\pi\tau}{T}\right)} \frac{\sin\left(\frac{n\pi t_r}{T}\right)}{\left(\frac{n\pi t_r}{T}\right)} \qquad (2)$$

$$\varphi_n = -n\pi\left(\frac{2\tau - t_r}{T}\right) \qquad (3)$$

where U_0 is the amplitude, T is the period, t_r is the pulse rising/falling time, t_0 is pulse wide, $= t_r + t_0$, n is the harmonic number, C_n is the amplitude of *n-th* harmonic, φn is the phase of *n-th* harmonic.

It can be seen from the above expansions, the amplitude of pulse spectrum is mainly related to U_0, τ, T and t_r. In this paper, the switching frequency of the pulse was set to 10 KHz, and a simulation study was carried out to analyze the effect of different parameters (listed in Table I) on the spectrum of trapezoidal pulse. As shown in Fig.2, the results demonstrate that high transient voltage will increases the amplitude of EMI and shifts the main interference to high frequency band.

TABLE I
SIMULATION PARAMETERS

Model	Amplitude U_0	Rising/falling time T_r	Duty cycle q $q=(2t_r+t_0)/T$
1	300V	0.1us	0.5
2	12 V	0.1us	0.5
3	300V	1us	0.5
4	300V	0.1us	0.2

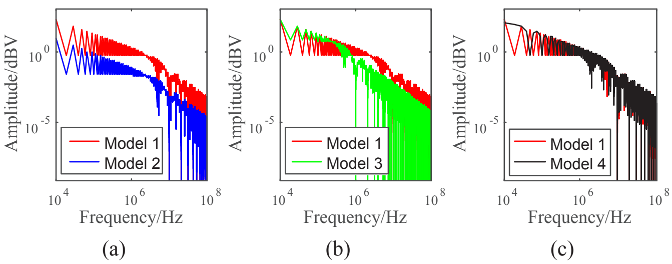


Fig. 2. The effect of different parameters on the spectrum of trapezoidal pulse. (a) Amplitude U 0 . (b) Rising/falling time T r . (c) Duty cycle q.

In addition to the effect of the power switch, motor windings will produce transient voltage and current fluctuation due to the sudden change of magnetic field in the process of starting, running and braking, and these interference signals will cause adverse effects on other devices through specific coupling paths.

2) Analysis of EMI Coupling Paths

According to the classification of coupling paths, EMI includes conducted interference and radiated interference, in which conducted interference can be further distinguished into differential mode (DM) and common mode (CM) [12].

For the motor driving system, the power switch is switched quickly according to the control strategy, which makes the inverter produce a periodic pulse current signal at the output port. The signal will form a loop through AC lines, the motor and batteries, and generates a DM interference current signal on the DC input side. As shown in Fig.3, the switch tubes S1, S5 and S6 are on-state, S2, S3 and S4 are off-state, and C2 is the capacitance between AC lines. The DM currents flow from the positive pole of DC bus to S1, and then to the negative pole of DC bus via the parasitic capacitance of IGBT, C2 and motor windings.

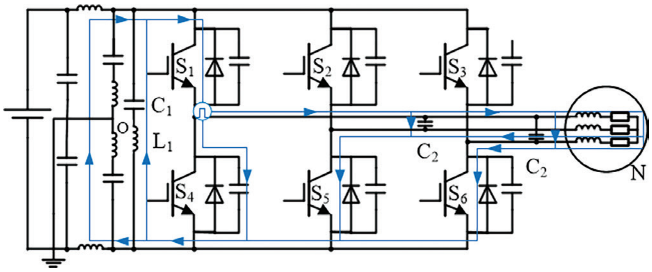


Fig. 3. The DM interference of the motor driving system

With regard to the CM interference, the power switch generates high du/dt at the moment of switching. The signal will charge the parasitic capacitance of components and generate high frequency oscillation as well. The CM coupling path of motor drive system is shown in Fig.4. In the figure, C3, C4, C5 and C6 are the parasitic capacitors of DC lines, inverters, AC lines and the motor shell to the ground respectively, O is the reference point. The CM currents form a closed coupling path through the capacitance C4, C5, C6 and motor windings.

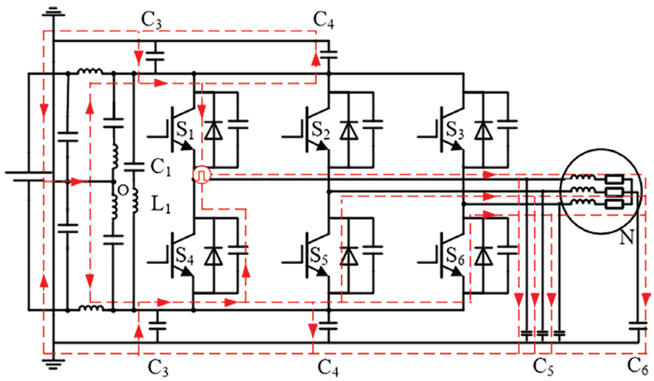


Fig. 4. The CM interference of the motor driving system

In addition, the DM/CM currents generated in the motor drive system will form a small loop antenna or wire antenna through cables, which can cause radiated interference to other systems or devices.

3) Measurements on the Motor Driving System

In order to investigate the EMC characteristics of motor drive system, this paper carried out a conducted emission test by the current probe method according to the CISPR 25 [13]. For conducted emission, the measured frequency is generally 150 KHz~108 MHz and the corresponding wavelength is 2000 m~3 m. A large number of basic experiments have proved that the disturbance signal in this wavelength range is most easily transmitted or coupled through wires. If the frequency is very high, the disturbance signal will directly spread to space and the will not be transmitted on wires. On the contrary, if the frequency is very low, the length of the wavelength is much longer than the length of the wires. In addition, considering the influence of test results on broadcast and mobile services and the limit requirements of CISPR 25, only the conducted emission of LW (150 KHz~300 KHz), MW (530 KHz~1.8 MHz), SW (5.9 MHz~6.2 MHz), CB(26 MHz~28 MHz), VHF(30 MHz~54 MHz and 68 MHz~87 MHz) and FM (76 MHz~108 MHz) were measured in this test. Moreover, as shown in Table and Fig.5, the inverter was in three working states: Power Switch-OFF, Power Switch-ON and FULL-LOAD operation of the motor.

TABLE II
EXPERIMENTAL PARAMETERS OF MOTOR SYSTEM

State	Motor Speed	Motor Torque
Power Switch-OFF	0rpm	0Nm
Power Switch-ON	0rpm	20Nm
FULL-LOAD	3000rpm	60Nm

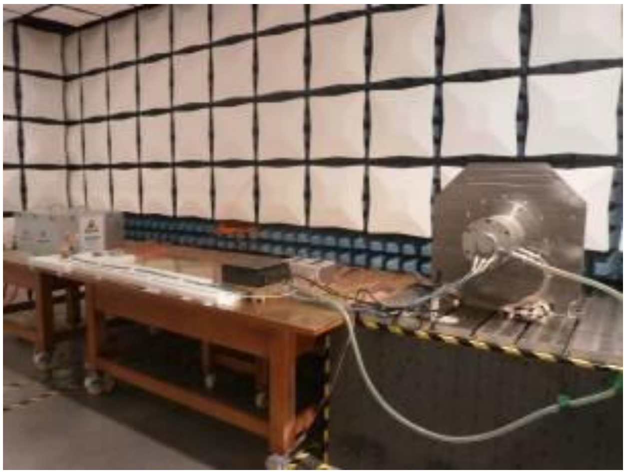


Fig. 5. Test setup for conducted emission

The result (see Fig.6) shows that the disturbance will increase significantly when the inverter is in the state of Power Switch-ON in the low frequency measurement range and besides 150 KHz~300 KHz, the additional electromagnetic disturbance will be introduced into the signal line when the driving motor is in the state of FULL-LOAD operation, which proves that the state of power switches and the operation of the driving motor are the main sources of electromagnetic interference in the motor driving system.

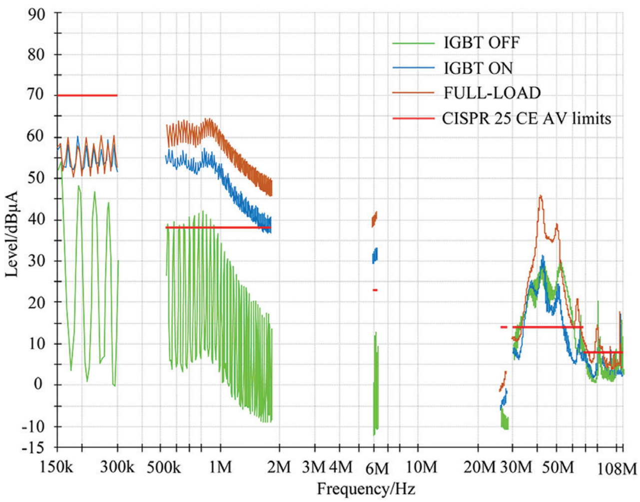


Fig. 6. Conducted emission of the signal line

B. Charging System

1) Characteristics of Disturbance Sources

There are two main ways to supplement the energy of electric vehicles: charging and battery swapping. As the battery swapping of electric vehicles mainly involves disassembly and installation, the EMC problems cannot be considered in particular. In addition, according to the way of energy coupling, the charging mode of electric vehicles can be distinguished into conductive charging and wireless charging, and the power conversion and transmission of the two charging modes are generally realized by the charging system.

Unlike the driving state, the charging system and the vehicle are directly connected to the power grid during the charging process. Therefore, the vehicle will face more serious EMC problems. On the one hand, the vehicle charging system will generate EMI signals, which will affect the electromagnetic environment outside the vehicle, especially the electromagnetic environment of the public power grid. On the other hand, the vehicle should be able to withstand the EMI from the external environment to ensure the charging safety.

EMC problems of charging systems usually involve rectifiers, inverters, control devices, charging modules, etc. Similar to the above, due to the quick switching of the power switch, the inverter will generate electrical interference signals with high transient voltage and large pulse current, which will become an important disturbance source in the charging system. In addition, the rectifier is a typical nonlinear device of the charging system, and it can generate a small amount of interference to the AC power grid and affect other equipment through power lines. In this paper, the emission of harmonic on AC power lines was measured respectively at the charging current of 12A and 28A, and the testing result is presented in Fig.7. As shown in the figure, the nonlinear effect of the charging system on power grid is closely related to the charging current, which means that electric vehicle will cause EMI in the charging process, and its influence will increase with the increase of current.

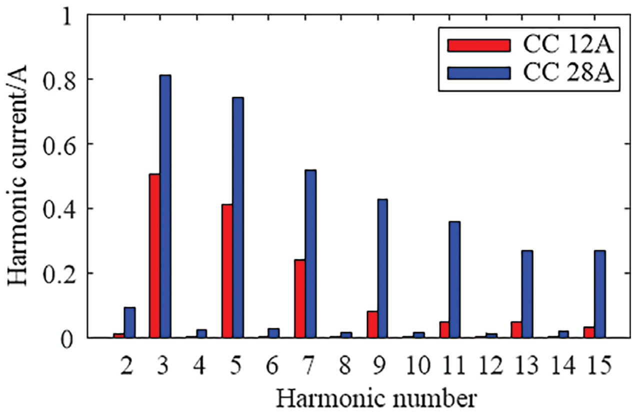


Fig. 7. Emission of harmonic on AC power lines from the charging system

2) Analysis of EMI Coupling Paths

Similar to the motor driving system, the conducted interference of the charging system can also be distinguished into DM interference and

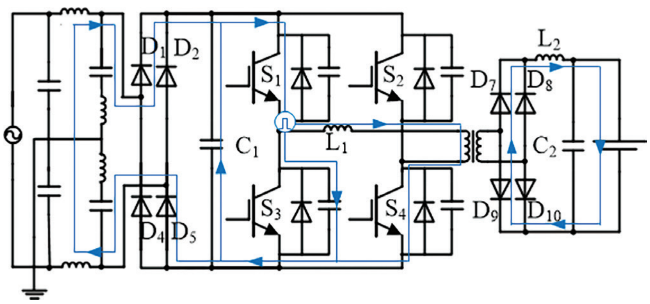


Fig. 8. The DM interference of the charging system

CM interference. As shown in Fig.8, when the conducted interference occurs in the system, the DM currents will form two loop antennas through the transformer and radiate the interference signal into space.

The CM interference coupling path of the charging system is shown in Fig.9. In the figure, C3 and C4 are parasitic capacitors of DC lines and inverter to the ground respectively. Since the transformer cannot be completely insulated from the ground, the CM current will cause some interference to the battery.

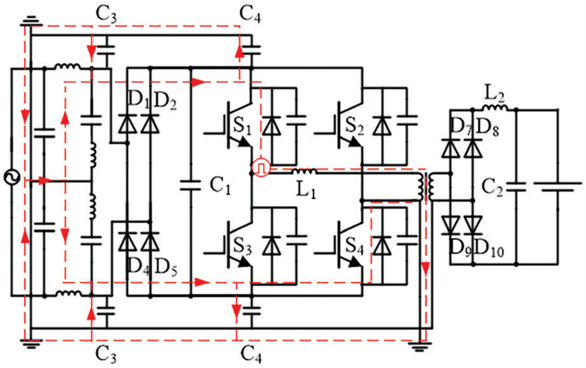


Fig. 9. The CM interference of the charging system

Compared with the conductive charging system, the main feature of the wireless charging system is to remove ferrite, and then use electromagnetic resonance technology to achieve energy transfer between the primary coil and the secondary coil [14-16]. In this case, the coils are in the state of intentional emission, and the electromagnetic radiated emission is more serious than that of the conductive charging system. With the exception of the difference, the energy transmission quality and electromagnetic radiated emission intensity of the wireless charging system are usually closely related to the operation state of the vehicle or the coils.

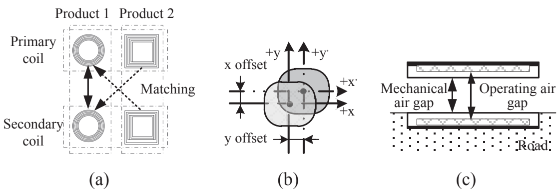


Fig. 10. Influencing factors of electromagnetic radiated emission for the wireless charging system. (a) Type. (b) Offset. (c) Clearance.

C. Other Systems or Components

In addition to the motor driving system and the charging system, electric vehicles have a large number of low-voltage electrical equipment. Although the power of these equipment is small, EMI will also occur directly or indirectly in actual operation. For example, (a) electric vehicles contain a variety of micro-motors [17], such as wiper motors, warm wind motors, air conditioning system motors, etc. These micromotors will interfere with other equipment due to the existence of transient voltage and brush sparking. (b) unlike conventional oil-fueled vehicles, the electric vehicles mostly use DC-DC conversion systems to provide power. And during the process of voltage conversion, the EMI signals will be introduced into the vehicles because of the transient changes of voltage and current [18].

III. Suppression and Optimization of Electromagnetic Compatibility for Electric Vehicles

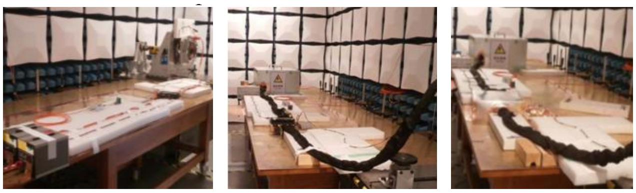
In order to solve the EMC problems, it is usually necessary to consider from three aspects: suppressing disturbance sources, optimizing EMI coupling paths and improving equipment immunity [12], and as far as the EMC problems of electric vehicles are concerned, the specific optimization measures mainly include grounding, filtering, shielding, rational layout and wiring of PCB, optimization of system principles, etc.

A. Research on the Cable Shielding

Low-voltage systems are required to resist internal and external EMI in the actual operation process. For most low-voltage systems of electric vehicles are control systems, and whether the control system works normally directly affects vehicle safety. However, with the use of high-power and high-voltage electrical components, electric vehicles are facing more safety issues as the high-voltage interference signals can affect low-voltage systems through cables.

Generally, in the design process of vehicles, the following design guidelines need to be considered: (a) the high-power circuit should be as close to the load as possible, (b) the cables with different functions or different power levels should be distinguished, (c) the signal lines and communication lines should be as far away from the main power lines as possible, and avoid parallel lines, (d) the shielded cables should be used to connect the motor driver and the motor, and the shield layer is grounded at both ends.

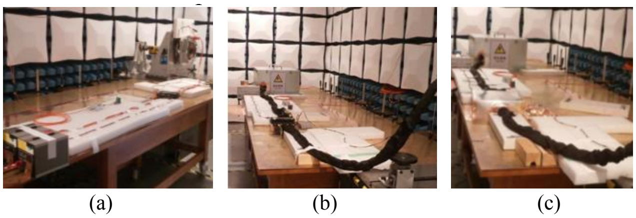
In this study, an experiment has been done to verify the validity of the cable shielding. As shown in Fig.11, the cables were shielded and unshielded respectively. In addition, considering the influence of the inverter, the inverter was shield by a metal box, and the connection between cables and the metal box was treated with silver paper. In order to better explore the influence of shielding on the results of radiation emission, the radiated emission in the full frequency range of 9 KHz~30 MHz was measured on the basis of product certification test requirements.



(a) (b) (c)

Fig. 11. Test layout of the research on the cable shielding. (a) The cables are unshielded. (b) The cables are shielded. (c) The cables and the inverter are shielded.

The test result is presented in Fig. 12 and it shows that the radiated emission decreases significantly when the cables are shielded below 10 MHz and the additional attenuation will be provided if the inverter is shield at the same time. What's more, although the radiation emission will be shielded by the metal box, some of the disturbance signals will still radiate through narrow gaps and may produce amplification effect if the disturbance signal wavelength matches the gap size, which leads to the attenuation between 1MHz and 3 MHz is lower than the scenario when the cable is shielded alone. Therefore, the shielding and ground-



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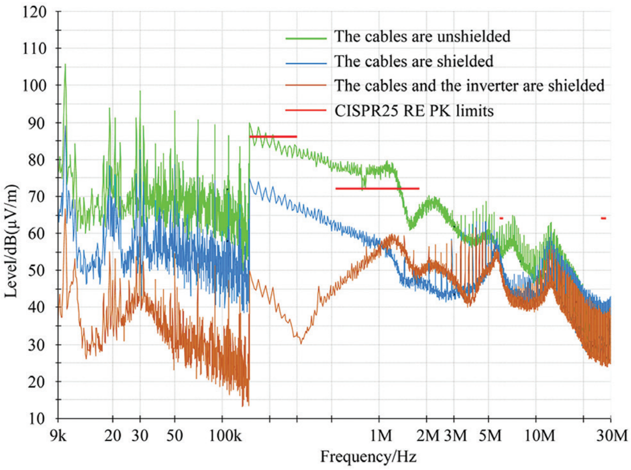

Fig. 12. Radiated emission at the range of 9 KHz~30 MHz

ing of the inverters should be given priority in the process of EMC optimization.

B. Research on the Optimization of System Principles

Through the study of the Cable Shielding and the simulation of the periodic ideal trapezoidal pulse wave, the switching frequency and the rising/falling time of pulse are the main influencing factors that affect the intensity of EMI signals, and the du/dt and di/dt by controlled by considering the measures such as changing the control strategy of the power switch, adding filter capacitances and changing the circuit structure of the system. In this paper, a sample of inverter under development was optimized by adding LC filter circuit. Compared with the original inverter, the optimized inverter is slightly different in the switching frequency, which lead to the rising and falling edges of the optimized inverters change more smoothly. The diagram of the three-phase inverter with LC filter circuit is shown in Fig. 13.

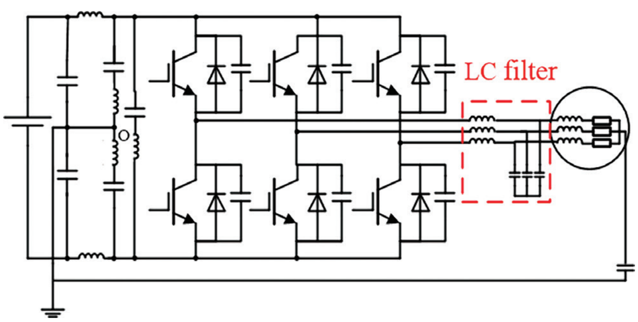

Fig. 13. Three-phase inverter with LC filter circuit

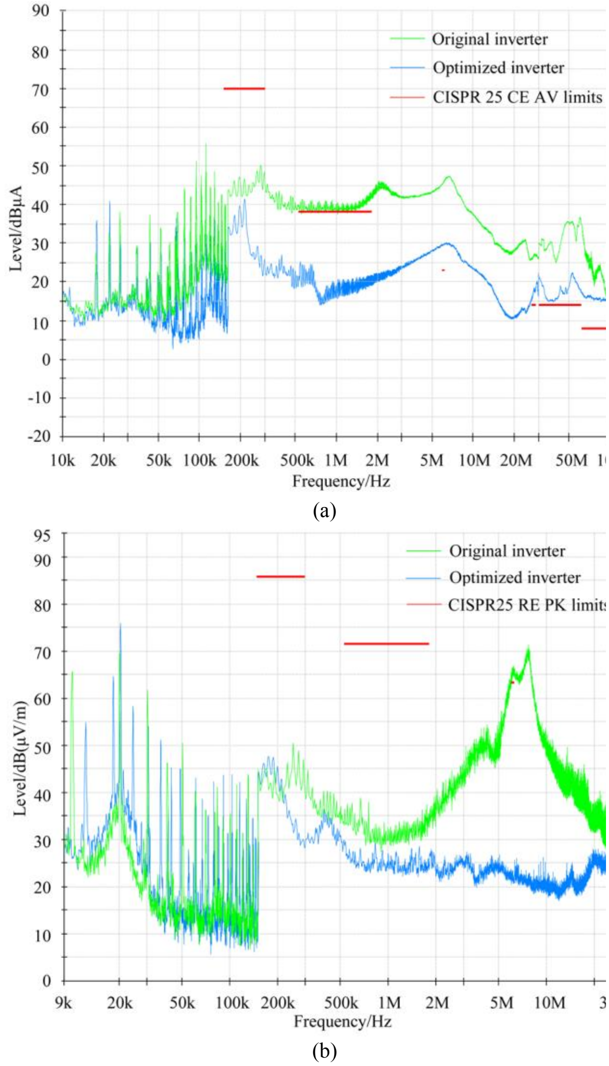

Fig. 14. Optimization of the inverter. (a) Conducted emission of the power line. (b) Radiated emission at the range of 9 KHz~30 MHz.

The test result is presented in Fig. 14 and it shows that LC filter circuit can reduce the conducted emission on the output side of the inverter and further affect the radiation emission of the motor or the system. In addition, LC filter circuit forms a small loop antenna, which results in the radiation emission of the optimized inverter is higher than that of the original inverter in the range of 150 HKz~200 KHz. Through the results mentioned above, although the efficiency is affected to some extent and the conducted emission does not meet the limit requirement in the frequency range above 6 MHz, the improvement effect of EMI is very obvious by only adding LC filter circuit.

IV. Conclusion

This paper introduces the EMC problems and investigates the EMI mechanism of motor driving systems, charging systems and other low-voltage systems. The analysis results show that the quick switching of power switches and the operation of motor windings are the main sources of EMI, and the EMI signals will propagate through cables or space to affect the surrounding electromagnetic environment as well as the normal operation of other electronic equipment. Furthermore, this paper studies the suppression and optimization measures for EMC problems of electric vehicles. Relevant experiments have been taken to prove that EMC problems can be solved effectively by taking optimization measures such as shielding, filtering and optimization of system principles.

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