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Overview of Research on EMC for Electric Vehicle Switching Power Supply

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Abstract. In view of the electromagnetic compatibility (EMC) problems existing in electric vehicle switching power supplies, this paper introduces the EMC characteristics of switching power supplies, expounds the electromagnetic interference (EMI) problems and interference mechanisms of switching power supplies, reviews the EMC predictive analysis methods of switching power supplies, and summarizes the EMI suppression technologies of switching power supplies. It is pointed out that establishing precise EMC simulation analysis models, conducting EMC scheme design and system optimization, and studying practical EMI suppression technologies for switching power supplies are urgent problems that need to be solved. This research on the EMC of electric vehicle switching power supplies has certain reference value.

Keywords: Switching power supply, EMC, Electromagnetic Interference, Pre-simulation, Electromagnetic interference suppression.

1. Introduction

With the widespread use of modern electronic devices and systems, the electromagnetic environment has become increasingly complex. Various electronic devices and systems coexist in the same space, and they may generate electromagnetic radiation and conductive interference, which may interfere with each other. In recent years, electric vehicles have entered a stage of rapid development, and the safety problems of electric vehicles have also attracted more attention.

Electromagnetic interference problems caused by electronic devices on electric vehicles may lead to the failure of vehicle electronic components, thereby affecting the normal operation of electric vehicles and causing safety hazards. There are many high-voltage components on electric vehicles, in addition to the electric air conditioning system studied in this paper, including the motor system, battery pack and BMS system, and the DC/DC module for converting high voltage to low voltage. The EMC characteristics of these high-voltage components are crucial to determining whether the electric vehicle's electromagnetic compatibility meets the requirements. The traditional vehicle's electromagnetic compatibility compliance rate is relatively high, reaching at least 80%, but the compliance rate of the electromagnetic compatibility of new energy vehicles is not optimistic, around 50%. Therefore, compared with traditional vehicles, it is imperative to improve the

EMC performance of new energy vehicles, and the key to improving the EMC characteristics of electric vehicles is to improve the EMC characteristics of high-voltage components. For EMC characteristics, professional electromagnetic compatibility standards have been formulated at home and abroad, and different components of automotive electronics have different testing standards and specifications. Currently, the international organizations that certify and manage include the International Electrotechnical Commission (IEC) and the International Special Committee on Radio Interference (CISPR). In the context of the rapid development of electric vehicles, domestic and foreign automotive industry standards have increased the EMC performance requirements for high-voltage components of vehicles.

2. Overview of Electric Vehicle Switching Power Supply EMC

2.1. Electric Vehicle Switching Power Supply

Switching power supplies are critical energy management components in electric vehicles, providing stable power support for various vehicle electrical systems by converting electrical energy efficiently. Switching power supplies operate on a "switching mode" basis, controlling the input current by rapidly switching on and off switching elements (such as MOSFETs) and filtering and stabilizing the output using inductors, capacitors, etc. Compared to traditional linear power supplies, switching power supplies have higher efficiency and can reduce energy loss and heat generation.

In electric vehicles, commonly used switching power supplies include Buck (step-down) converters, Boost (step-up) converters, and Buck-Boost (boost-step-down) converters.

The Buck converter is suitable for situations where the voltage needs to be reduced, such as offline power supplies for electronic products, battery-powered circuits, and local regulators. A synchronous Buck converter can be built, and if the output current of a single-stage circuit is too large, a multiphase Buck converter can be used. In the Buck converter, there are two main loops where the current changes rapidly (di/dt), as shown in Figure 1. When the field-effect transistor Q1 in the circuit is turned on, current flows out of the power supply, through Q1 and L to the output capacitor Co and the load R, and then back to the power supply output terminal through the ground. During this process, the alternating current component flowing through the input capacitor Cin and the output capacitor Co is shown by the current path i1.

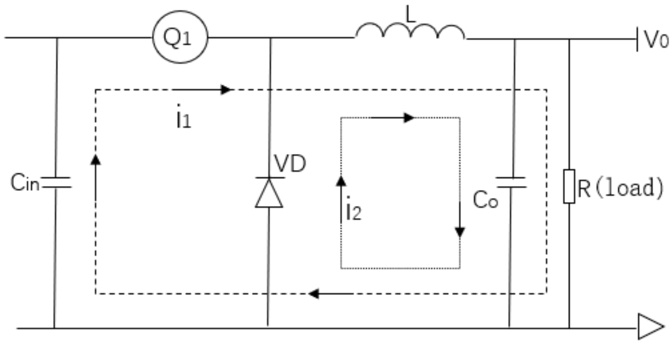

Figure 1. Current loop of Buck circuit.

Unlike Buck converters, Boost converters are used in systems where the output voltage is higher than the input voltage. For example, battery-powered systems or those that require providing a local, appropriate high voltage use switching elements (such as transistors) and energy storage elements (such as inductors and capacitors) to perform voltage conversion.

The Buck-Boost converter combines both functions, increasing the input voltage or decreasing it. The transmitted voltage is negative with respect to ground, which is considered a disadvantage of this converter topology. Therefore, this structure is currently used less in electric vehicle switching power supplies.

2.2. Electric Vehicle Switching Power Supply EMC Environment

Due to the high voltage, large current, and complex structure of electric vehicles, their electromagnetic interference (EMI) energy is larger, the frequency band is wider, and the propagation coupling path is diverse, which increases the difficulty of EMC research for motor drive systems. However, in terms of the basic nature of EMI, the EMI of motor drive systems is the same as that of other electronic devices or systems. It is composed of three basic elements: electromagnetic interference sources, propagation paths (or coupling channels), and susceptible bodies (sensitive bodies), as shown in Figure 2. Therefore, by cutting off any one of the three links, the EMI problem of the motor drive system can be solved.

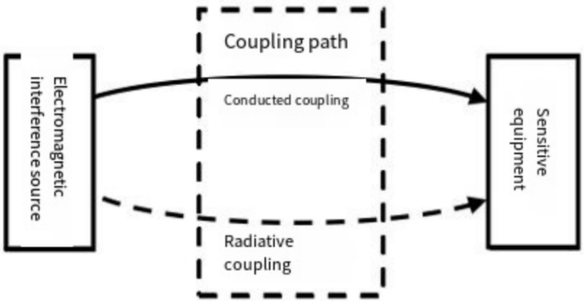

Figure 2. Three elements of electromagnetic compatibility.

2.2.1. Electromagnetic Interference Source

Interference sources include narrowband interference sources (such as digital logic circuits in vehicle electronic components that include clocks, crystals, microprocessors, and displays) and broadband interference sources (such as motors and ignition systems). Specific examples include IGBT power modules in motor controllers, MOSFET power modules in DC-DC converters, and clock circuits in vehicle control units. The time-domain characteristics and frequency-domain characteristics of interference source signals are different, and various interference source signals act on the high-voltage system and low-voltage system of the vehicle at the same time. Currently, interference source modeling is usually done using linear ideal interference sources, which have significant differences from actual interference sources.

2.2.2. Coupling Pathway

High-voltage and low-voltage components are arranged in the limited space of the vehicle, and the position and length of the components and cables will affect the conduction and radiation coupling paths. Electromagnetic interference transmission electromagnetic coupling paths are often modeled using lumped circuit models, which ignore or simplify parasitic parameters and distributed parameters, making the electromagnetic interference path analysis incomplete or incorrect, and therefore cannot accurately and effectively represent, predict, and suppress electromagnetic interference noise signals.

According to the different transmission modes of EMI, it is divided into common-mode (Common Mode, CM) interference and differential-mode (Differential Mode, DM) interference. They have different internal mechanisms. The main cause of common-mode interference sources is the high du/dt in the circuit, which charges and discharges the parasitic capacitance, and the high-frequency common-mode current flows through the phase line, the parasitic capacitance, and the ground to form a circulating loop. Differential-mode interference refers to the interference between the phase lines, which is caused by the pulsating current di/dt generated by the inverter during operation, and it directly forms an interference loop through the phase lines and the power supply. The transmission paths of differential-mode interference and common-mode interference are shown in Figures 3 and 4. When the circuit interference is above 30 MHz, the interference source will propagate electromagnetic waves in space to the affected equipment.

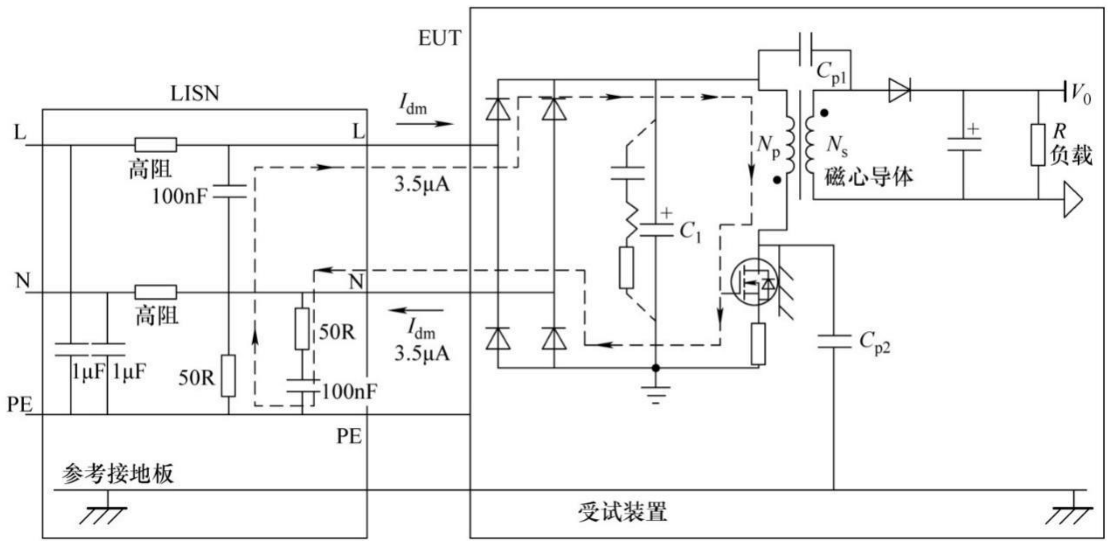

Figure 3. Differential mode interference in switching power supply.

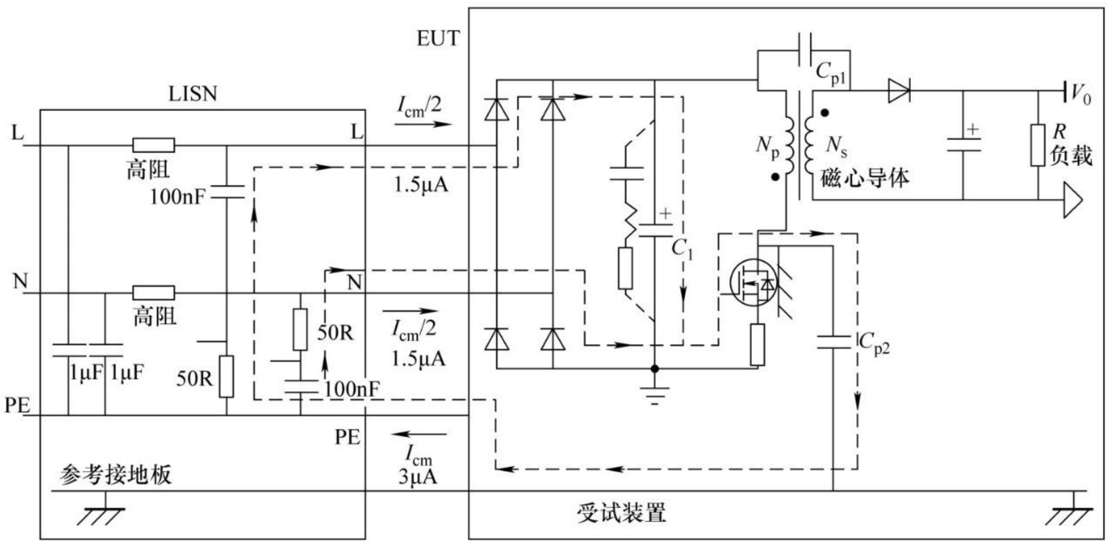

Figure 4. Common mode interference in switching power supply.

2.2.3. *Disturbed Sensitive Source*

Sensitive equipment is diversified, such as intelligent sensors such as radar, safety controllers such as ABS, vehicle controllers, battery management systems, various radio receiving equipment, etc. During the actual operation of the vehicle, the high-voltage power system will cause electromagnetic interference to sensitive equipment such as intelligent sensors, electronic controllers and actuators through high-voltage cables and vehicle CAN bus network. At the same time, smart sensors and on-board wireless communication devices will also produce radiation disturbance signals.

3. Electromagnetic Interference of Switching Power Supply and Its Mechanism

3.1. Research on Electromagnetic Interference of Switching Power Supply

Electromagnetic interference (EMI) refers to the undesired electromagnetic signal interference phenomenon caused by the interaction and coupling of electromagnetic fields in electronic devices and systems. There has been significant progress in the study of electric vehicles at home and abroad, while the research on the EMC of electric vehicle switching power supplies is relatively short. In the early stage, the research mainly focused on the study of electromagnetic interference and its mechanism.

The research on the EMC of switching power supplies in developed countries started earlier, and they have achieved more research results than ours. Saponara S et al. established a high-frequency interference model of switching power converter transformer and predicted the interference over-standard frequency band through simulation of the conducted interference of switching power supply, and proposed suppression measures to verify the effectiveness of suppression measures [1,2]. DNDalal et al. studied the influence of the parasitic parameters of the components in the switching power supply on the conducted interference amplitude, making the interference prediction model of the switching power supply closer to reality [3]. However, it did not consider the influence of parasitic parameters on the conducted interference at different frequencies. Keita Takahashi et al. proposed a noise model using voltage source and current source to simulate noise with voltage dependence and current dependence, making the noise source model established more comprehensive and scientific [4]. SepehrKarimi estimated the size of the stray capacitance on the common-mode interference path using the unscented Kalman filter method and established a real-time common-mode interference prediction model to achieve accurate prediction of the common-mode interference of the switching power supply [5].

The research on electromagnetic compatibility in China started later, and it has relatively backward research equipment and technology level. However, with the development of China's science and technology, China's research on electromagnetic compatibility has also developed rapidly. Wu Hao studied the switching power supply from the perspective of forward design, selecting the appropriate components, shielding, grounding, and routing measures [6]. Yu Bo studied noise suppression from the board level based on the BUCK power circuit of the switching power supply [7]. Wen Tao and others used predictive methods based on electromagnetic field simulations to establish an equivalent model of the near-field radiation of a PCB, locating and analyzing the sources of electromagnetic interference on the PCB board of a switching power supply, and improving the electromagnetic compatibility of the switching power supply by optimizing the layout and routing of PCB components [8]. Liu SiRui of Harbin University of Industry based on the simulation results of the conducted electromagnetic interference of a switching power supply and combined them with test modeling to construct a fault-test correlation matrix for conducted electromagnetic interference, obtained the optimal fault diagnosis tree, set up a test platform and verified it [9].

The switching power supplies used in electric vehicles are often based on isolated topology, and the high-frequency transformer inside is also a major electromagnetic interference source. Lin Subin of Fuzhou University derived the mathematical model of the common-mode port effective capacitance of a flyback transformer, set up a demonstration platform for the common-mode characteristics of a flyback transformer based on network analyzer, and proposed a simple experimental testing method. Through case studies, experimental conditions were provided to support the analysis [10]. At the same time, Lin Subin worked with Zhou Yun and others to view the transformer as a common-mode filter, clarifying the interference sources that affect the common-mode noise of the transformer, and by designing a more optimal winding structure, changed the distributed capacitance parameters between the windings, improving the common-mode interference characteristics of the transformer [11]. Xu Ce and others considered the frequency characteristics of the magnetic field and established a model that can reflect the characteristics of the wide-band magnetic field of the transformer, which can accurately predict and evaluate the common-mode performance and resonance point of the transformer over a wide frequency range [12].

3.2. Research on Electromagnetic Interference Mechanism of Switching Power Supply

Currently, the research on electromagnetic interference mechanisms at home and abroad is mainly focused on the sources of interference and the transmission paths. The frequency spectrum characteristics of the electromagnetic interference noise emitted by the interference source are analyzed, and the coupling of the electromagnetic transmission path is analyzed to derive an equivalent transmission path diagram to explore the mechanism of electromagnetic interference. Since 1960, foreign professional scholars have made electromagnetic compatibility an independent discipline and conducted in-depth research and analysis. China has also gradually attached importance to research on electromagnetic compatibility and has formulated relevant electromagnetic compatibility specifications and requirements based on various situations. After the research of various scholars, differential interference has been finely divided into common-mode interference. The path of interference has been separated and analyzed separately for common-mode and differential-mode loops. The common-mode path is formed by the positive and negative wire and ground loop. Differential interference is transmitted along the wire between the positive and negative terminals.

The earliest traceable literature dates back to 1993, when Sankaran V. A. and others proposed that the high-speed switching action of IGBT may cause EMI problems and that it is necessary to study the feasibility of applying soft switching technology in the drive system inverter circuit [13]. In 1995, Zhong E. K. and others determined through experiments that the inverter system would generate considerable pulse currents and be introduced into the system through cables, causing serious conduction EMI problems and voltage waveform distortion in the power system [14]. In 1997, Lai J. S. used an auxiliary switch and a resonant inductor on each phase to enable the main switch to open at zero voltage, and conducted actual tests on a 100 kW three-phase inverter. The simulation and measurement results confirmed that soft switching technology can reduce EMI [15]. In 2001, Dong W. and others verified through experiments that the auxiliary quasi-resonant inverter can reduce EMI, but this type of soft switching inverter is only effective at 2-10 MHz, and considering factors such as cost, size, and efficiency, this type of soft switching inverter is not suitable for electric vehicle drive systems

[16]. In 2003, Guttowski S. et al. studied the EMI problems caused by the installation of a new power-driven system in traditional passenger cars [17]. In 2007, Nelson J. J. et al. pointed out that transient operation of the drive system, such as load torque and speed gradients, would cause more serious EMI problems [18]. Song Tianhao from Zhejiang University based on the dynamic differential evolution algorithm source reconstruction method for electromagnetic interference diagnosis, quickly and accurately locates the dipole position, and represents the real electromagnetic interference source in a continuous wide frequency band [19]. Gu Long from Chongqing University used wavelet decomposition to extract the interference source from the electric vehicle converter and determined which frequency band the electromagnetic interference was serious and verified that the interference-generating components were power switching tubes [20]. Qu Jianshuai from Hebei Industrial University set up a DC/DC converter conduction interference test platform for electric vehicles and studied the conduction interference of the control signal duty cycle and the measurement cable at different positions, and concluded that the control signal duty cycle affects the source of electromagnetic interference and the reasons for the difference in the size of the interference [21]. Zhang Qing's knowledge graph-based electromagnetic interference localization method has shown better results than traditional localization methods through experimental results [22].

4. Research on EMC Pre-simulation of Switching Power Supply

The automotive industry is facing relatively high costs for EMC testing, and it is difficult to pass the test with just one test. If the test fails, further improvements are needed to enhance EMC performance, and professional testing environments are rare in China, making it expensive to set up such environments. Many car manufacturers resort to repeated testing on-site, which leads to a long project development cycle and high costs, and may even fail to meet the EMC standard requirements. Therefore, since the 1980s, foreign researchers have begun to conduct simulation studies on the electromagnetic interference generated by the ignition system of automobiles. Initial research used high-frequency circuit models to model the electromagnetic interference generated by automotive electronic devices. With the development of the computer industry, various numerical calculation solver software was developed and widely used in the commercial sector, and EMC simulation analysis has gradually become accessible to the general public.

4.1. EMC Analysis Method

Because EMC problems involve a wide range of knowledge and require high-precision testing, no simulation software has been developed that can analyze all aspects of automotive EMC performance. Different software with different emphases is needed to solve the EMC performance problems of different parts of the car. The following are the main categories of analysis methods currently in use [23, 24, 25].

The first category is the HFSS software based on the Finite Element Method (FEM), developed by the American company Ansoft. This software has comprehensive functions for analyzing microwave engineering problems, easy-to-use interface, accurate calculation results, and is recognized as a three-dimensional electromagnetic field design and analysis software by engineers and researchers.

The second category is the CST software based on the Finite Integration Technique (FIT) time-domain algorithm. CST has a total of eight subsidiary studios, including PCB studio, microwave studio, and design studio, etc. The operation interface of CST is very similar to that of WORD, making it easy for users to get started. The software's various subsidiary studios can be combined for simulation, and it has both time-domain and frequency-domain solvers, making it very convenient to process simulation results. The frequency solution range covers both low and high frequencies, and can accurately solve problems in all frequency bands.

The third category is the FEKO software based on the Method of Moments (MOM). This software is the first to apply the Method of Moments to commercial simulation software. Its feature is that it can accurately analyze large electromagnetic problems, and it has many electronic modules from the automotive field that can be used, so it is also widely used in the automotive industry.

Simulation predictions usually require selecting the appropriate calculation method based on the focus of the actual problem [26]. The electromagnetic compatibility of automotive electronic components includes complex circuit problems and electromagnetic field problems, which are difficult to solve directly through simple models and general methods. The hot spot in the field of automotive electromagnetic compatibility is to build compatibility simulation models of automotive electronic components while ensuring accuracy, and to complete electromagnetic compatibility simulation predictions of automotive electronic components.

4.2. EMC Pre-simulation Analysis

Regarding the electromagnetic compatibility (EMC) simulation analysis of pure electric vehicles, with the widespread application of simulation software, the accuracy of the models has become increasingly higher [27]. By establishing an electromagnetic radiation testing platform for electric vehicles and calculating the transfer function, the size of the common-mode current-induced electromagnetic field can be obtained. By using numerical algorithm simulation calculation, the consistency between the transfer function and the test data is verified, thereby validating the effectiveness of the transfer function [28]. However, this method cannot be effectively applied to the derivation of transfer functions for multi-wire bundles.

Literature [29] used an improved dual-current probe method to quickly and accurately measure the amplitude and phase of the common-mode and differential-mode circuit impedances of the DC/DC converter in an electric vehicle. Literature [30, 31] determined the different impacts of parasitic capacitance parameters on the common-mode EMI of the motor drive system when the PWM inverter worked at low-frequency band and high-frequency band. At low-frequency band, the influence of the AC cable-to-ground parasitic capacitance parameter on the common-mode EMI is greater; at high-frequency band, the influence of the IGBT heat sink-to-ground parasitic capacitance parameter on the common-mode EMI is greater. Literature [32-35] proposed different suppression methods that can effectively suppress the propagation of electromagnetic interference sources. Literature [36, 37] conducted electromagnetic compatibility simulation and experimental testing of the electric drive system to verify the accuracy of the model. Literature [38] conducted electromagnetic compatibility simulation and testing of the entire vehicle. Literature [39] proposed the TDR time-domain reflection method based on the analysis of transmission line theory. Literature [40] analyzed the high-frequency parameters of the interference path using the TDR method and conducted electromagnetic interference analysis on the interference path of the inverter and motor. Literature [41] designed a filtering circuit at the port of the power conversion circuit and verified the effect using MATLAB/Simulink software. It proposed the relationship between time and frequency on electromagnetic interference. The paper [42] analyzed the influencing factors of conducted emission based on the working principle of the inverter from the perspectives of filtering parameters and parasitic parameters. Huang Yanqiong and others [43] established a vehicle wiring simulation analysis method to enhance the ability to manage the risk of inter-wire crosstalk in the EMC design stage.

To sum up, at present, the research on EMC prediction and simulation of electric vehicle switching power supply at home and abroad has made certain progress and results, respectively using different numerical methods or analytical ideas to conduct EMC modeling and simulation research on a single component of switching power supply or the whole system. EMC pre-simulation research of EV switching power supply shortens the product development cycle, saves the cost, and provides a scientific analysis method and means to solve the EMI problem of EV switching power supply.

5. Research on Electromagnetic Interference Suppression of Switching Power Supply

There are three main methods to suppress the electromagnetic interference of switching power supply, which are shielding, grounding and filtering. Usually in engineering, shielding and grounding measures are used to suppress electromagnetic interference. These two methods are to suppress electromagnetic interference by cutting off the interference path. Filtering is to reduce the interference voltage and current emitted by the interference source, reduce the emission intensity of the interference source, and inhibit the electromagnetic interference caused by the interference source.

Another common method of EMI suppression in switched-mode power supplies is to cut off the path of electromagnetic interference sources. Scholars from various countries have proposed various EMI filter structures for blocking the path of EMI propagation. Experimental results show that properly designed filters can reduce the EMI emission intensity of motor drive systems to below the EMC standard limit value, making it an important means of achieving EMC for electrical equipment and systems. Weber T. studied the EMC filters for a 600V DC-connected traction drive system with multiple types of EMI filters and introduced a new type of magnetic bypass common-mode choke [44]. Von J. A. et al. analyzed the EMI current on the motor side from the perspective of eliminating common-mode EMI current, and added a 4th winding with a terminating damping resistor wrapped around the same core as the common-mode choke to suppress the oscillation of common-mode EMI current [45]. Ogasawara S. et al. combined a Pi-type passive EMI filter and an active common-mode noise eliminator to propose an improved Pi-type active EMI filter structure. This structure can eliminate the common-mode voltage induced on the induction motor end while suppressing the harmonics of the PWM power converter [46]. Jiang Baojun from Harbin Industrial University proposed a passive common-mode EMI filter structure for the DC/AC output end based on the formation mechanism of common-mode voltage and current on the induction motor side of the system, which overcomes the disadvantages of traditional power converter output end passive common-mode EMI filters with poor frequency characteristics and large size [47]. Liu Jinfeng from Harbin University of Science and Technology conducted a thorough analysis of the electromagnetic interference sources and propagation mechanisms of the drive control system and proposed a feedforward active EMI filter, and conducted a comprehensive and systematic analysis of the structure, parameters, and performance of the filter [48].

Reducing the emission intensity of interference source is a common method of EMI suppression technology. Trzynadlowski A. M. et al. used Saber simulation software to make A comparative analysis on EMI reduction between random PWM modulation and ordinary PWM modulation, and pointed out that random PWM modulation can reduce about 10 dB EMI noise compared with ordinary PWM modulation, and has almost no impact on drive performance [49]. Muton N. et al. proposed an EMI suppression method by encapsulating the inverter power supply circuit through multilayer printed circuit boards to suppress common mode current. Later, based on the series resonance phenomenon, the author proposed a method to eliminate the surface current in the positive and negative power cables between the inverter and the battery, and the effectiveness of this method was verified by experiments [50, 51]. Lai Y. S. took advantage of the fact that different combinations of vector states would affect the output common-mode voltage of power converter, and proposed space vector modulation technology. Two vector flyback methods in opposite directions were adopted to replace the function of zero vector, so as to reduce the system common-mode voltage and achieve the purpose of suppressing EMI [52]. Zhang H. R. et al. proposed a two-bridge power converter for eliminating common mode voltage and shaft current in motor drive systems. By controlling the two-bridge power converter to generate a standard three-phase double-winding induction motor balance excitation, the common mode voltage can be offset to achieve the purpose of reducing the leakage current and EMI emission intensity [53]. Dou Ruzhen et al. proposed a novel space vector pulse width modulation control method based on common mode current and voltage harmonics caused by common mode voltage, which can effectively reduce the common mode voltage of asynchronous motor drive system powered by voltage source inverter.

In summary, the research on electromagnetic interference suppression technology of switching power supply has made some achievements. Most of the research focuses on the suppression of common-mode conduction electromagnetic interference of switching power supply, because in electromagnetic interference, common-mode conduction interference is the most harmful, and radiation interference is also mainly caused by the existence of common mode interference. In addition, many of the above electromagnetic interference suppression technologies, in view of the structure, cost and other aspects of the reasons, still cannot be well applied to engineering practice, therefore, seeking engineering practical and effective electromagnetic interference suppression technology is also a development direction of electric vehicle switching power supply EMC research.

6. Conclusion

In recent years, the EMI mechanism research of switching power supply has gradually matured, but the research of EMC predictive modeling simulation and EMI suppression technology is still in the process of development. Because of the complexity of EMI mechanism and system of switching power supply, it is very difficult to model accurately. How to establish an accurate EMI prediction simulation model and guide engineering application effectively is still an urgent problem to be solved. In addition, the EMI suppression technology of switching power supply mostly stays in the laboratory research and exploration stage, and has not yet formed a more complete solution. How to fully consider the EMC characteristics in the product design and application process, and form the corresponding design theory and specification should be a problem that needs to be solved in the future engineering applications.

Based on the relevant literature, this paper summarizes the electromagnetic interference and its mechanism, pre-simulation research, electromagnetic interference suppression and other aspects of switching power supply for electric vehicles, and puts forward the key problems and development trends in the study of switching power supply EMC, which provides a reference for the research and engineering application of switching power supply EMC for electric vehicles.

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