Research Progress of Electromagnetic Interference Suppression in Power Converters

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Abstract. In this paper, the related concepts of Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) were expounded, the research progress of EMI suppression methods for power converters was summarized, and the future development trend of EMI suppression for power converters was pointed out, for example, EMI suppression method of changing circuit topology, EMI suppression method for improving control strategy, EMI suppression method of optimized driving circuit.

1. Introduction
Power converter can be defined as a multi port circuit composed of semiconductor switching devices and auxiliary devices (capacitors, inductors, transformers, etc.). Its main function is to realize the energy conversion between two or more subsystems in the expected way according to the preset performance index. Generally, power converters can be classified according to the types of electrical subsystems they are connected to, such as DC-DC converter, DC-AC converter, AC-DC converter and AC-AC converter. With the development of power semiconductor device technology, thyristors, bipolar transistors, power MOSFETs and other devices have promoted the improvement of circuit topology of low and medium power converters (several w to dozens of KW). In the field of high voltage and high power applications, the invention of these devices also gave birth to some new topologies that can make full use of the characteristics of the devices.

EMC of power converter is a comprehensive subject, involving device physics, circuit theory, electromagnetic field theory, testing technology, etc. At present, the research on EMC of power converter is still in the primary stage. As far as EMI is concerned, there is no essential difference between EMI generated by power converter and that in other power electronic equipment or systems. However, due to the topology and components of power converter, its electromagnetic interference has its own characteristics. The power semiconductor device in power converter works in the switch state, which determines that its voltage and current waveforms have wide-band spectrum, which is the source of electromagnetic interference. With the improvement of the performance of power converter, the switching frequency and power density of the converter are increasing, resulting in more and more complex electromagnetic environment inside the equipment.

The research on EMC of power converter has become one of the hotspots in the field of power electronic technology. In this paper, the related concepts of EMI and EMC were expounded, the research progress of EMI suppression methods for power converters was summarized, and the future development trend of EMI suppression for power converters was pointed out.

2. Related concepts of electromagnetic interference and electromagnetic compatibility
Since Faraday proposed the law of electromagnetic induction, human society has entered a new stage of electric power application. The invention and application of various power electronic equipment have greatly promoted the development of society. Some equipment need to radiate electromagnetic energy to the environment in normal operation, such as radio equipment, radar equipment, navigation equipment, etc.; others unintentionally radiate electromagnetic energy to the environment when completing normal tasks, such as ignition system, converter and some control equipment. The sum of electromagnetic phenomena existing in the working environment constitutes the electromagnetic environment, which is an important part of modern society, and also the basis of analyzing electromagnetic interference and electromagnetic compatibility.

Electromagnetic disturbance refers to any kind of electromagnetic phenomenon that may cause the performance degradation of a device, equipment or system in the electromagnetic environment. The degradation of device, equipment or system performance caused by electromagnetic interference is called electromagnetic interference (EMI) [1] - [4]. According to the definition, whether it is a complex system or a simple system, electromagnetic interference must have three elements:

a. Interference source refers to the device, equipment or system generating electromagnetic disturbance;

b. Sensitive equipment refers to the device, equipment or system affected by electromagnetic disturbance;

c. Coupling channel refers to the transmission path of electromagnetic disturbance from interference source to sensitive equipment.

d. Generally, according to the propagation mechanism of electromagnetic interference, electromagnetic interference is divided into two categories:

e. Radiated electromagnetic interference, which is caused by electromagnetic wave propagating through space, such as broadcasting, radar equipment, signal generator, ignition system, etc;

f. Conduct electromagnetic interference, which is caused by the coupling of wires, capacitive devices or inductive devices, such as various oscillators, relays, semiconductor devices, etc.

The response characteristics of devices, equipment or systems to electromagnetic disturbance are called electromagnetic sensitivity. The simultaneous interpreting mechanism of electromagnetic disturbance can be divided into radiosensitivity and conduction sensitivity.

According to the definition of electromagnetic interference and electromagnetic sensitivity, electromagnetic compatibility (EMC) refers to the electromagnetic interference that devices, equipment or systems can work normally in their electromagnetic environment and cause to other equipment in the environment within the allowable range.

3. Research status and development trend

There is no essential difference between the EMI produced by power converter and that produced by other power electronic equipment or systems. The generation of EMI needs three elements: EMI source, EMI propagation path and sensitive equipment. Therefore, the research on the methods of EMI suppression can start from the three elements of EMI, that is, reducing the intensity of the interference source and cutting off the transmission path. EMI filtering technology is an EMI suppression method based on cutting off the transmission path, which is one of the most important and effective means to suppress conducted electromagnetic interference. However, with the development of power converter to high frequency, miniaturization and high power density, EMI filter is not suitable for the current development trend due to the limitation of volume and weight. Theoretically, as long as the EMI emission intensity of the interference source is reduced, the EMI of the system can be effectively reduced. The voltage and current waveforms of power semiconductor devices, i.e. switching waveforms, are the source of electromagnetic interference in the converter. So we can change the
circuit topology, improve the control strategy and optimize the driving circuit to affect the switching waveform, so as to suppress the electromagnetic interference.

3.1. EMI suppression method of changing circuit topology
The main idea of improving the circuit topology is to eliminate the common mode voltage of the converter output through symmetrical structure, and reduce the level of conducted interference emission on the input side of the device due to the halving of the voltage change rate on the switch device.

In the early research, Julian led scholars proposed a three-phase four leg scheme to eliminate the output common mode voltage of three-phase power converter according to the "circuit balance principle" [1] - [3], as shown in figure 1. The basic idea of the method is to use an additional "auxiliary phase" to make the three-phase system circuit symmetrical to the ground potential, and by adjusting the switch sequence, the sum of the four bridge arm output phase voltage is zero as far as possible, so as to realize the common mode voltage is zero completely. Compared with the traditional three leg power converter, its common mode EMI can be reduced by about 50%. Manjrekar [4] and Rao [5] proposed a scheme to eliminate the common mode voltage caused by the zero switch state by adding auxiliary zero state switch. This method of auxiliary zero state synthesizer is very attractive in economy, and it can also eliminate the common mode voltage of induction motor side.

![Fig. 1 Four-leg inverter with second-order filter and motor load](image)

Compared with the traditional power conversion, although the three-phase four leg and auxiliary zero state synthesizer can eliminate or reduce the common mode voltage of the system, their modulation strategies will reduce the system voltage utilization. Therefore, Haoran Zhang [6] - [8] and other scholars proposed a double bridge power converter for eliminating the common mode voltage and shaft current of the motor. It can generate standard balanced excitation of three-phase double winding induction motor by controlling double bridge power converter, and cancel common mode voltage through balanced excitation (magnetic system), so as to eliminate shaft voltage, shaft current and fully reduce leakage current and EMI emission intensity. In order to eliminate the common mode current of PWM motor drive system, based on the common mode voltage compensation technology, Consoli [9] and other scholars proposed a common mode current elimination technology applied to the common DC bus of multi drive system composed of two or more power converters. This method is a new PWM modulation strategy which makes the common mode voltage change synchronously by controlling the state sequence of the two converters on the basis of the proper connection of the two power converters. To sum up, changing the circuit topology can effectively suppress the common mode EMI in the power converter, but it also complicates the original converter topology. At the same time, new control strategies need to be developed according to the new topology.

3.2. EMI suppression method for improving control strategy
Because the two-level PWM modulation strategy will inevitably make the output of power converter contain common mode voltage, some scholars propose some new modulation strategies which can eliminate or reduce the common mode voltage based on improving the inverter control mode or strategy.

In the early research, Taipei scholar yen Shi Lai [10] - [11] proposed the space vector modulation technology. This method uses the characteristics that different combinations of vector states will affect the output common mode voltage of the power converter. Two opposite direction vector "flyback" methods are used to replace the role of zero vector, so as to reduce the common mode voltage of the system and achieve the purpose of suppressing conducted EMI. However, broe [12] and other scholars put forward a space vector modulation method of synchronous change of switches on the rectifier side and the inverter side, which can avoid generating common mode voltage pulse with the same size as the DC bus voltage; the Korean scholar hyeoum Dong Lee [13] has changed the space vector modulation method of full control three-phase rectifier / inverter, which is based on the movement of non-zero vector position to reduce the output common of the system Based on the principle of the number of mode voltage pulses and the action time, the common mode voltage can be reduced.

In addition, some scholars propose to apply spread spectrum technology to EMI suppression of power converter. As early as the mid-1990s, some scholars used the spread spectrum modulation technology in communication system to reduce EMI emission. In the early research on power converter EMI suppression by spread spectrum technology, TSE [14] and other scholars applied a random carrier technology to the conducted EMI suppression of off-line switching power supply, and made theoretical analysis in the time and frequency domain. Santolaria [15] and other scholars have theoretically analyzed the influence of switching frequency range and modulation profile on the suppression effect of switching frequency modulation EMI. Gonzalez [16] and other scholars applied the periodic switching frequency modulation technology to the conducted EMI suppression of power converter, and pointed out that the random frequency modulation can only evenly distribute the spectrum energy in the spectrum range, while the periodic frequency modulation can control the bandwidth of EMI energy distribution. In recent years, santolaria [17] and other scholars have analyzed the influence of switching frequency modulation on the output voltage of power converter. Dousoky [18] and other scholars have put forward some new spread spectrum schemes and made theoretical analysis. The conducted EMI suppression of DC-DC power converter is realized by FPGA chip.

3.3. EMI suppression method of optimized driving circuit

Because the DV / dt and di / dt caused by the high-frequency switching action of power semiconductor devices in power converter are too large, their size and high-order harmonics directly affect the emission intensity of EMI system. Moreover, for common switching devices, the magnitude of DV / dt and di / dt at the switching moment is affected by the gate driving waveform and gate stray capacitance [19]. Therefore, if we only consider from the perspective of reducing EMI emission intensity, we can reduce DV / dt and di / dt by selecting appropriate circuit topology and control strategy, so as to reduce EMI emission intensity of the system. Lobsiger [20] and other scholars put forward a new IGBT driving circuit. Through a PI controller, the di / dt and DV / dt of IGBT can be controlled respectively. The drive circuit uses closed-loop control to compensate the nonlinearity of IGBT, and can adjust the slope of voltage and current according to the set value. IDR [21] and other scholars put forward a new active grid voltage control method. By directly changing the shape of the grid input voltage, the di / dt at on and DV / dt at off are controlled. The drive circuit can reduce the overshoot current caused by the reverse recovery of the continuous current diode in the opening phase, and also reduce the output voltage oscillation when the diode is turned off. The gate control signal may be realized in a very simple way with a voltage divider of ratio as indicated on Fig. 2. Kagerbauer [22] and other scholars proposed an active gate drive circuit to control DV / dt of MOS transistor by changing Miller capacitance. The relationship between EMI and switching loss is analyzed theoretically.
Costa [23] and other scholars analyzed the switching waveform (voltage or current waveform of switching device) in time and frequency domain, and pointed out that the high-frequency electromagnetic interference intensity generated by the switching waveform is closely related to the number of its conductivity. Assuming that the switching waveform has k-order derivative at most, the slope of the asymptote of the high frequency spectrum is \(-20(K + 1) \text{ dB / Dec.}\) The active voltage control (AVC) proposed by Palmer [24] and other scholars can effectively control the transient waveform of IGBT collector voltage, making the collector voltage waveform follow the predefined reference signal. According to the research results of Costa, Palmer and other scholars, Patin [25] and other scholars proposed a Gaussian switching waveform with infinite order derivative, and a closed-loop gate drive (clgd) with similar structure to AVC to control the drain source voltage shape of power MOSFET. The simulation results show that the EMI generated by drain source voltage of power MOSFET is significantly reduced under the control of closed-loop gate control circuit compared with hard switch. However, the switch waveform does not meet the continuous condition. Yang [26] and other scholars optimized the AVC circuit proposed by Palmer, shaping the emitter voltage waveform of IGBT into the Gaussian switch waveform proposed by Patin, and the EMI suppression effect is significant.

The current research focuses on the closed-loop gate drive circuit for IGBT. The switching on and off process of power MOSFET and IGBT are basically similar. However, due to the current tailing phenomenon of IGBT, the switching time of IGBT is longer, resulting in the lower frequency of IGBT driving pulse, which makes it easier to control IGBT in the active area. The power MOSFET has higher switching time and frequency, and higher on resistance, which makes it difficult to design the closed-loop gate driver circuit for power MOSFET. Generally speaking, this method has a good effect of suppressing EMI, but compared with hard switch, its switching time is longer, resulting in increased loss; moreover, due to the nonlinear problem of semiconductor devices, the stability design of driving circuit is very important; the voltage utilization rate is reduced, and the efficiency of converter is reduced.

4. Conclusion
With the development of power electronic technology, all kinds of power electronic equipment are widely used in various fields of modern society. With the increasing power density and switching speed of power electronic devices such as power converters, the volume of equipment and system is decreasing, and the problem of electromagnetic interference is becoming increasingly prominent. EMI filter technology is one of the most important and effective means to suppress conducted electromagnetic interference, but with the development of power converter to high frequency, miniaturization, high power density and other directions, passive EMI filter is limited by volume and weight, and does not adapt to the current development trend. Active power filter (APF) has a broad application prospect because of its active cancellation technology. The methods of reducing EMI by reducing the interference source, such as changing the circuit topology, improving the control strategy and optimizing the driving circuit, have become a research hotspot.

5. References
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