E3S Web of Conferences **256**, 01006 (2021) https://doi.org/10.1051/e3sconf/202125601006
PoSEI2021

Predictive Model for Conducting Electromagnetic Interference by Bidirectional Excitation Controller

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Abstract. Bidirectional excitation controller is used in the excitation system of brushed DC motor. There are many monitoring sensors and weak current switches nearby. Therefore, it is necessary to study the conduction interference of the excitation controller. Firstly, based on the working principle of bidirectional excitation controller, the propagation path model and corresponding equivalent circuit of bidirectional excitation controller are established. Then, the parasitic capacitance parameters between the switch tube and the heat sink were extracted by ANSYS Q3D software, and the dynamic model of IGBT was established by using ANSYS Simplorer software. Based on ANSYS software, the prediction model of the equipment conducted electromagnetic interference was obtained. Finally an excitation controller conducting interference test platform was built, and the predicted results were compared with the measured interference results of the experimental platform to verify the accuracy of the prediction model.

1Introduction

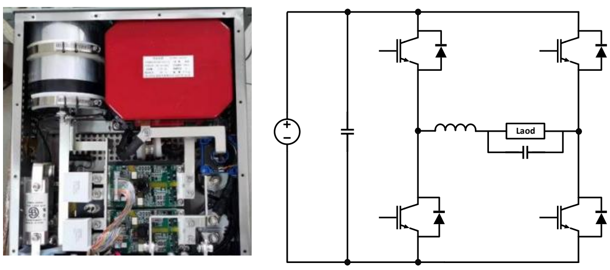
When the power electronic devices work, the voltage and current are often very high, and the power electronic devices are in the high frequency disconnection state. The dv/dt of FF450R12ME4 IGBT module used in the excitation controller is up to 3100V/μs and di/dt is up to 7000A/μs during the switching process. They form flow paths to conduct EMI with the stray capacitors and stray inductors of the equipment respectively. On the power grid side, the electromagnetic interference directly affects the sensitive equipment connected to the power grid through the ship power grid. On the load side of the motor, the high-frequency common-mode interference noise forms displacement current through the parasitic capacitor between the winding and the motor shaft. The long-term action of displacement current will cause serious electrochemical corrosion on the motor bearing and affect the service life of the motor [1]. If accurate conduction interference prediction model is established, EMC design efficiency will be greatly improved.

In literature [1-3], the modeling of interference sources is based on the actual measured time domain waveform, which can only be carried out after the completion of equipment manufacturing and debugging. Moreover, the accuracy of measuring instruments is extremely high, so interference prediction in a real sense cannot be realized. Although a model of IGBT interference source is proposed in literature [3], the proposed method is still based on the measurement results of the device. Literature [4] proposes a behavior model of IGBT to simulate the switching voltage and current of actual devices. This improved and simplified EMI modeling method can also better predict the EMI spectrum even when the working conditions change.

The prediction model of conducted electromagnetic interference introduced in this paper only needs to measure the selected devices to predict the EMI noise of the equipment in the early stage of product design. The influence of circuit structure and control mode on the conducted EMI can also be optimized based on software. At the same time, when the model is used in conjunction with the finite element software in the process of EMI filter design, the EMI design efficiency of equipment will be greatly improved.

2Bidirectional excitation controller

2.1Principle



(a) Physical map (b) Circuit schematic

Figure 1. Bidirectional excitation controller

The topology of this two-way excitation controller is the H-bridge type DC-DC circuit topology. The rated output power is 7.2kW, the rated input voltage is 200V, the working frequency of the IGBT is set to 10kHz, to meet

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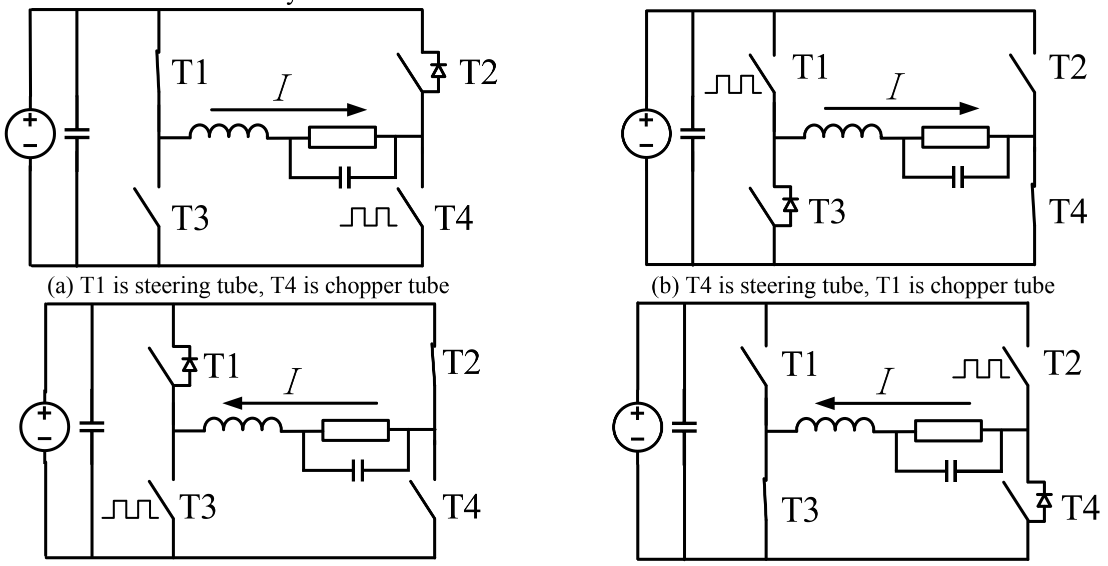
https://doi.org/10.1051/e3sconf/202125601006

the motor speed, the output current is in the range of 5A-40A Adjustable. The working state of the two-way DC-DC transform circuit in the two-way excitation controller is shown in Figure 1, and can be divided into a forward circulation and reverse flow in the current flow direction.



(a) T1 is steering tube, T4 is chopper tube (b) T4 is steering tube, T1 is chopper tube

(c) T2 is steering tube, T3 is chopper tube (d) T3 is steering tube, T2 is chopper tube

Figure 2. Operation mode of bidirectional excitation controller

No matter which mode of operation, the spectrum of conducted interference is theoretically the same. The working state in Figure 2 (a) is selected for circuit principle analysis. T1 is the directional tube to control the flow direction of the current, T4 is the chopper tube to adjust the output voltage, and T2 is the reverse parallel diode to serve as the continuation diode.

2.2Conducted interference analysis

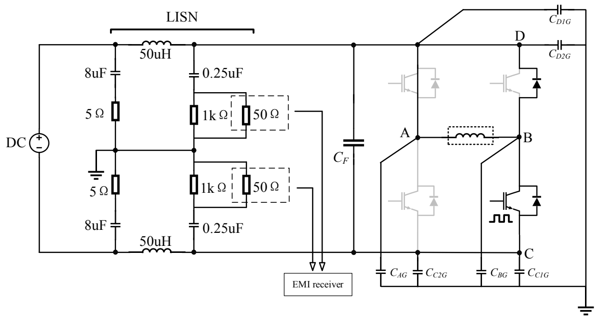
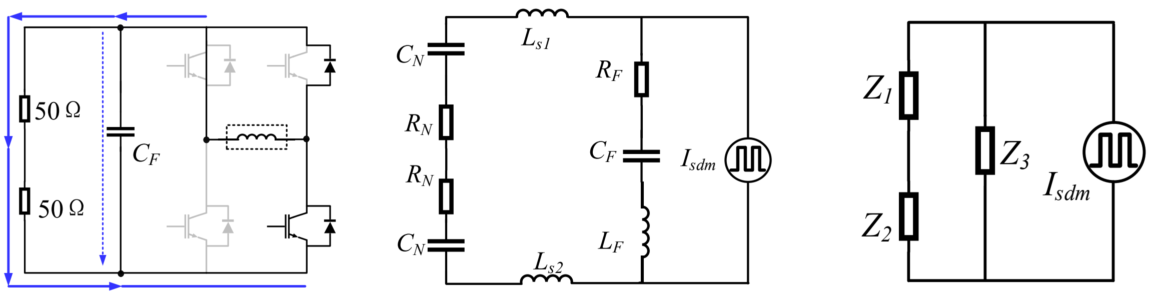


Figure 3. Propagation path model of conducted interference in motor excitation controller

The coupled path model of the conducted interference of the bidirectional excitation controller is shown in Figure 3, which is mainly composed of power supply, LISN, power input cable, H-bridge DC-DC conversion circuit, IGBT and parasitic capacitance and load of ground. According to different conduction paths, EMI interference can be divided into differential mode form and common mode form. The differential mode EMI conduction path and common mode EMI conduction path are discussed separately in the following sections.

2.2.1Differential mode interference



(a) Coupling paths (b) The equivalent circuit (c)Simplified circuit

Figure 4. Differential mode EMI

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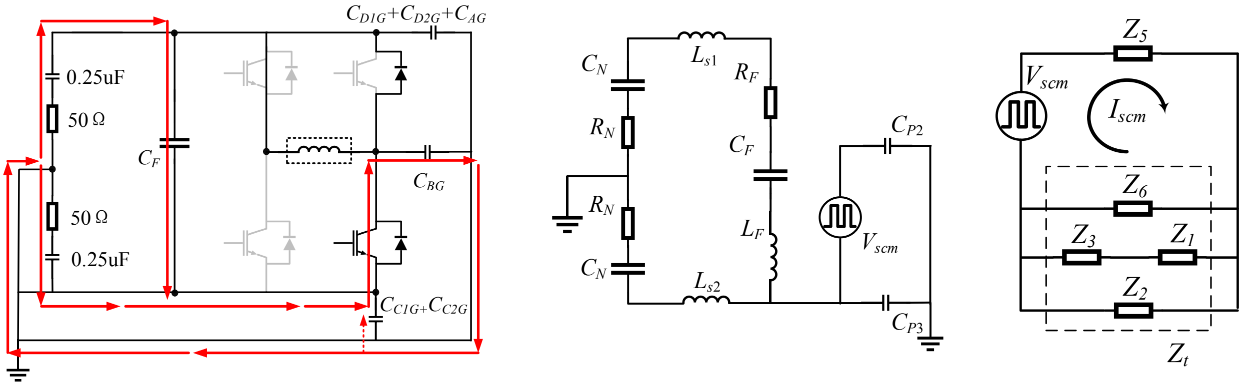
Figure 4 shows the propagation path and equivalent circuit of differential mode interference, and I_{sdm} is a current source of differential mode interference. To analyze and calculate, the equivalent circuit is simplified, and then simplified as shown in Figure 4 (c). The voltage calculation expression of differential mode interference is as follows:

$$V_{dm} = \frac{2R_N Z_3}{Z_1 + Z_2 + Z_3} I_{sdm} \tag{1}$$

2.2.2Common mode interference

The coupling path and equivalent circuit of common mode interference are shown in Figure 5. Vsdm is the current source of differential mode interference, CP2 is the parasitic capacitance to ground of AC part of IGBT module, and CP3 is the sum of the parasitic capacitance to ground of DC part of the lower tube of two IGBT modules. In order to facilitate analysis and calculation, the equivalent circuit is simplified, as shown in Figure 5 (c). The calculation formula of current I_{scm} generated in the loop by voltage source V_{scm} of common mode interference can be expressed as:

$$I_{scm} = \frac{V_{scm}}{Z_5 + Z_t} \tag{2}$$



(a) Coupling paths (b) The equivalent circuit (c) Simplified circuit

Figure 5 Common mode EMI

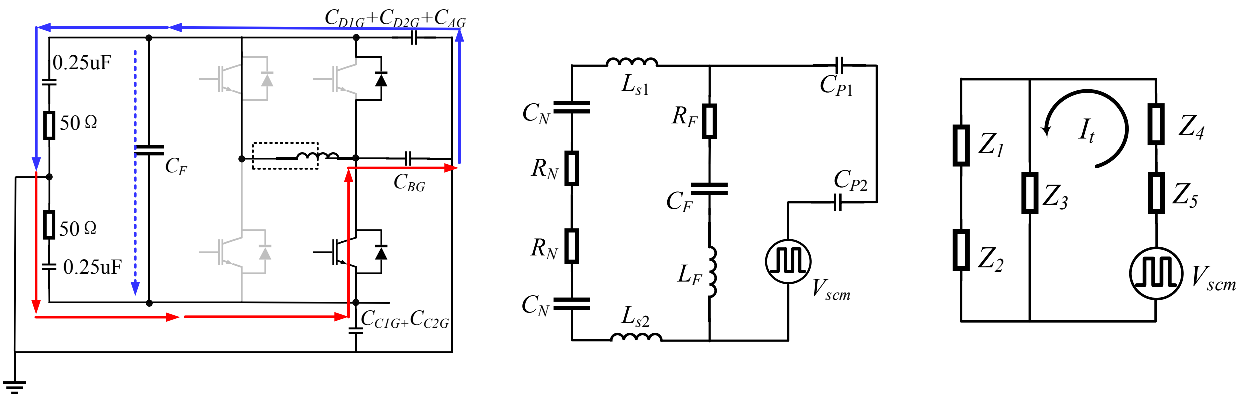
where

$$Z_t = Z_6 // Z_2 // (Z_1 + Z_3) \tag{3}$$

Therefore, the common mode voltage detected on LISN can be expressed as:

$$V_{cm} = \frac{0.5R_N}{Z_5 + Z_t}\left(V_{scm} - I_{scm}Z_5\right) = \frac{0.5R_N Z_t}{\left(Z_5 + Z_t\right)^2} V_{scm} \tag{4}$$

2.2.3Common mode interference to differential mode interference



(a) Coupling paths (b) The equivalent circuit (c) Simplified circuit

Figure 6 Common mode interference to differential mode interference

Because the impedance distribution of the common-mode interference circuit is unbalanced, the common-mode interference is converted to differential mode interference, as shown in Figure 6. C_{P1} is the sum of parasitic capacitance to ground of DC part of upper channel of two IGBT modules and parasitic capacitance to ground of AC part of directional control IGBT. The parasitic capacitance value is large, which becomes the main coupling path of conversion from common mode interference to differential mode interference. In order to facilitate analysis and calculation, the equivalent circuit is simplified, as shown in Figure 6 (c). The voltage source of common-mode interference (V_{scm}) generates conversion current (I_t), and its calculation formula can be expressed as:

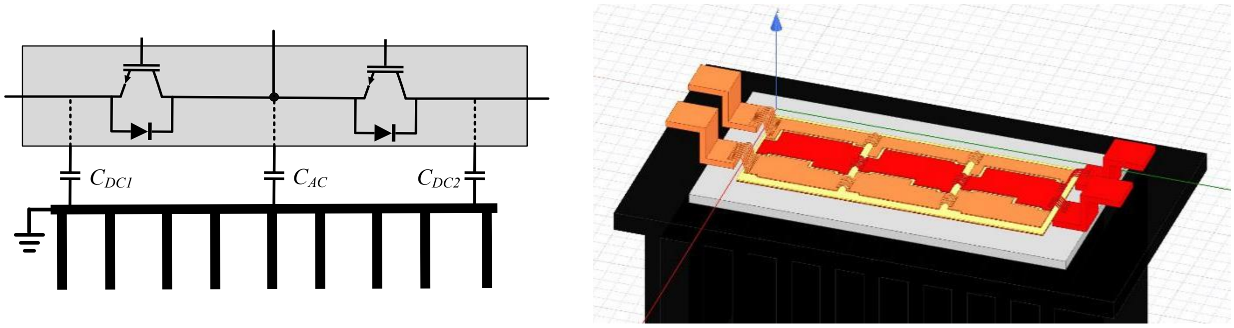
$$I_t = \frac{V_{scm}}{Z_4 + Z_5 + Z_3 // (Z_1 + Z_2)} \quad (5)$$

Thus, the differential mode voltage detected by Rn on LISN can be expressed as:

$$V_{cm-dm} = \frac{2R_N}{Z_1+Z_2}\left[V_{scm} - (Z_4+Z_5)I_t\right] = \frac{2R_N}{Z_1+Z_2}\left[1 - \frac{(Z_4+Z_5)}{Z_4+Z_5+Z_3//(Z_1+Z_2)}\right]V_{scm} \quad (6)$$

3Prediction model

3.1Parasitic capacitance extraction of switch tube and heat sink



(a) Capacitance distribution (b) 3D model

Figure 7 Parasitic capacitance of switch tube and heat sink

Accurate extraction of the parasitic capacitance between the switch tube and the heat sink is very important for the simulation prediction of the conducted interference. For the calculation of parasitic capacitance between IGBT device and radiator fin, the extraction methods used in some existing literatures are not accurate. If we want to extract the parasitic capacitance accurately, we must first understand the IGBT packaging process. The correct definition of the parasitic capacitance should be the capacitance value between the upper copper layer and the heat sink. The lower copper layer, the lower solder layer and the copper substrate in the middle of the two should be understood to be in a state of suspension and have no effect on the capacitance value.

According to the package parameters in IGBT data manual, the 3D model of IGBT module and heat sink is established in ANSYS Q3D, and the model is shown in Figure 7. According to the simulation results, parasitic capacitance parameters are obtained. the parasitic capacitances C_{DC1} and C_{DC2} of the DC part of IGBT are 186.51pF and 283.23pF, the parasitic capacitance C_{AC} of the middle AC part is 296.63pF, and the sum of the parasitic capacitances of the three parts is 766.37pF.

3.2Dynamic model of IGBT

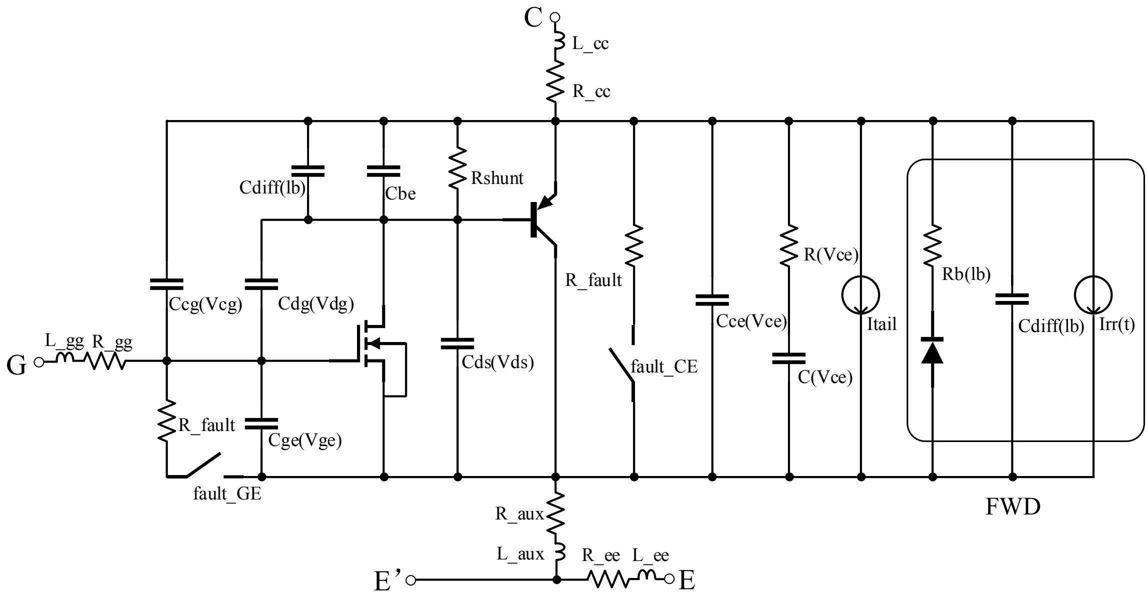


Figure 8 Equivalent circuit of the IGBT model

Isolated gate bipolar transistor IGBT (Insulated Gate Bipolar Transistor) is a composite device, whose input control part is MOSFET and output power part is BJT. Although IGBT is a voltage control device, the junction capacitor needs to be charged in the process of voltage rise, which still needs a certain current to realize.

The type of IGBT used in this bidirectional excitation controller is FF450R12ME4. In order to simulate and predict conduction EMI more accurately, the power semiconductor characteristic modeling tool in Ansys Simplorer software was used to establish the dynamic model of IGBT. The equivalent circuit diagram of the IGBT model used was shown in Figure 8. According to the data manual, enter the values of the convergence target of the model, such as E_{on}, E_{off}, T_{on} and T_{off}. Under the test condition of half bridge circuit, the parameters in the dynamic model were iteratively extracted according to all kinds of input data, and the final results met the accuracy requirements.

3.3Simulation prediction model

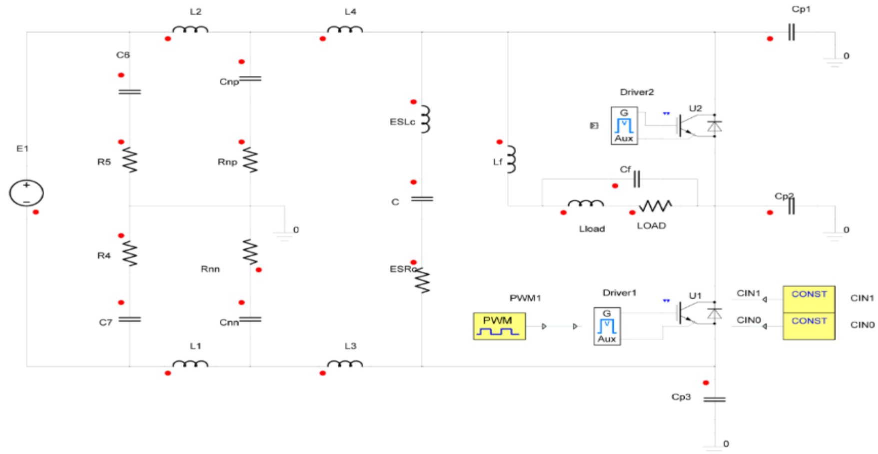


Figure 9 Simulation Model of Conducted EMI for Motor Excitation Control

The conduction interference prediction model of bidirectional excitation controller was built in Simplorer, as shown in Figure 9.The IGBT drive PWM signal frequency is set at 10kHz, the switch level is +15V, the switch resistance of the gate drive is 2.8Ω, the switch level is -15V, the switch resistance of the gate drive is 3.75 kV. The transient simulation was carried out. The simulation step size was set as 1ns-10ns and the simulation time was set as 5ms.The voltages on the 50Ω resistors in two LISN are picked up, and then FFT transformation is carried out to obtain the conducted interference of the two power supply input lines respectively. The interference spectrum is the red line in Figure 11, which is the conducted interference spectrum obtained by simulation of the prediction model.

4Experimental verification

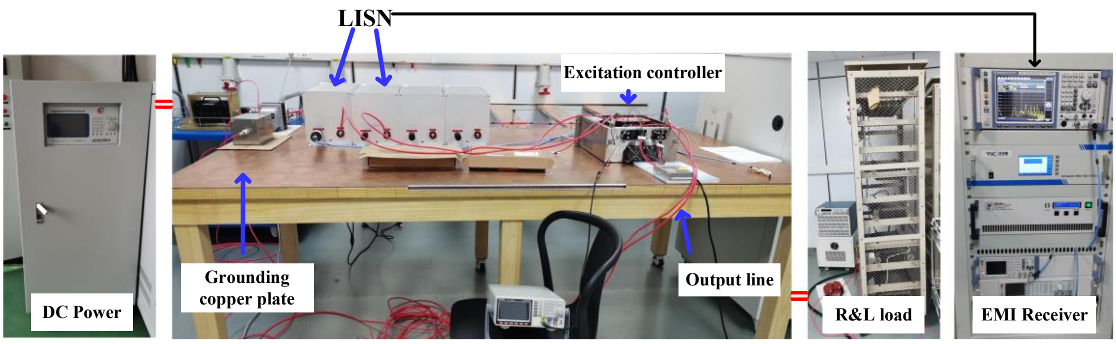


Figure 10 Experimental platform of bidirectional excitation controller conducting EMI

The object of this research is a bidirectional excitation controller with rated power of 7.2KW. The load is connected with resistive load. In order to verify the accuracy of the established conducted EMI prediction model, the conducted interference test of the two-way excitation controller was carried out in the EMC shield room. According to the layout standard of CE102 test item of GJB151B-2013, an experimental platform for two-way excitation controller conducting EMI test was arranged in the EMC shield room, as shown in Figure 10. For the measurement of the interference spectrum, the standard requirement is that the EMI receiver is set as the peak detection mode. Conducted interference spectra of two power supply input lines are obtained on two LISN channels in the bidirectional excitation controller conducted EMI experimental platform, as shown in the black line in Figure 11.

In the figure, the blue line is the limit requirement of GBJ151B-2013 for conducting interference to equipment. In the frequency range of 10kHz-500kHz, the simulated and measured values are basically consistent. In the frequency range of 500kHz-10MHz, the error values are all within 9dBμV, which indicates that the conducted interference prediction model of the bidirectional

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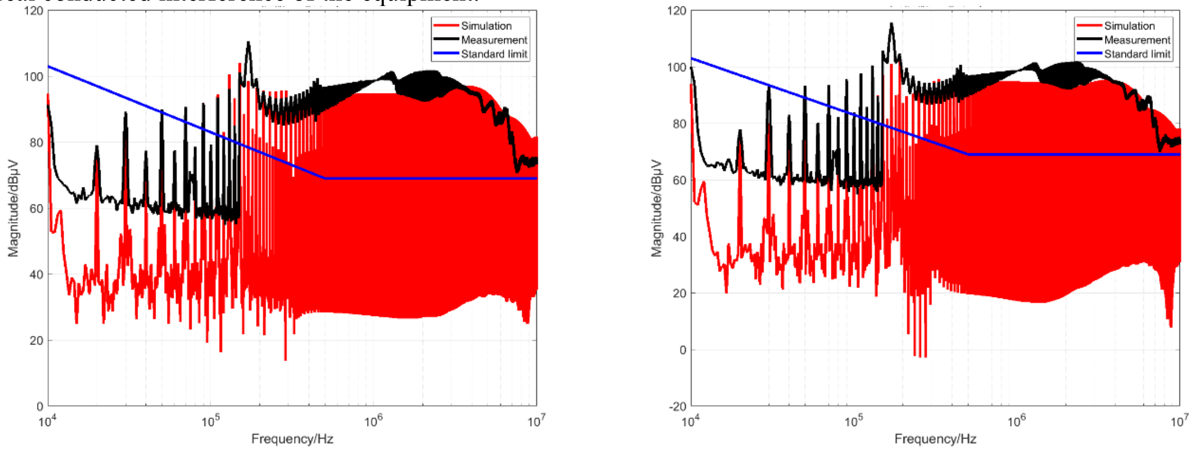
excitation controller has a high accuracy and can simulate the real conducted interference of the equipment.



(a) Interference spectrum of positive power line

(b) Interference spectrum of negative power line

Figure 11. Comparison between simulation and measurement of conducted interference of bidirectional excitation controller

5Conclusion

On the basis of mastering the working principle of bidirectional excitation controller, the propagation path of conduction EMI of bidirectional excitation controller is analyzed, and the corresponding equivalent circuit model is established. Impedance analyzer was used to measure the parasitic parameters in the circuit and finite element method was used to extract the parasitic parameters in the circuit. The dynamic model of the used IGBT module was established by using the characteristic modeling tool in Simplorer, and then all the models were connected to form the conduction EMI prediction model of the bidirectional excitation controller. A two-way excitation controller conducted EMI test platform was built in the EMC shielding room. The measured voltage spectrum of the conducted interference was basically consistent with the prediction model, which verified the accuracy of the prediction model.

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