A Series-Winding Topology Converter for the Magnetic Field Superimposed Magnetic Bearing

Jianfu DING, Dong JIANG, Zicheng LIU

Huazhong University of Science and Technology, No.1037, Luoyu Road, Hongshan District, Wuhan, China, djf@hust.edu.cn

Abstract

The power electronic drive is an essential component of a magnetic bearing system. It can rapidly change the current of the windings, thus controlling the dynamic changes of the electromagnetic force. This paper proposes a novel magnetic bearing power electronic drive based on a series-winding topology mainly used for magnetic field superimposed magnetic bearings. This topology can control the windings' bidirectional current and can be extended to an N-degree-of-freedom system with only 2N+2 switching devices. Compared to the conventional topology, this topology can reduce the cost of the drive, ensuring the current control capability. Moreover, this topology structure can evenly distribute the current of each winding between the bridge legs, reducing the current stress of the bridge legs compared to the common bridge-leg structure. The basic properties and control strategies of the series-winding topology are analyzed. Experiment and work verify the availability of the topology.

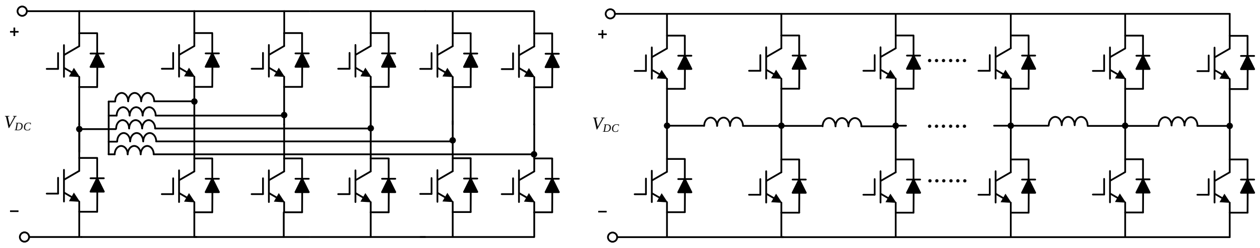
Keywords: *Magnetic Bearing, Series-Winding Topology, Power electronic drives*

1. Introduction

Magnetic bearing (MB) is a key technology of the high-speed rotational machine. The power electronic drive is an essential part of the MB system. Its performance directly determines the control performance of the suspension system and has a decisive impact on the control accuracy and maximum speed [1].

According to the output current direction, the topology of the MB switching power electronic drive can be divided into two categories: unipolar and bipolar. The output of the former is a single-direction flow, which is used to supply power to the current superimposed MB, while the latter can be a two-way flow, which is used to supply power to the magnetic field superimposed MB [2]. Many scholars have worked on unipolar switching power amplifiers [3]. For bipolar topology, the full-bridge circuit is the most widely used. However, each load current needs four switches for regulation, which is costly.

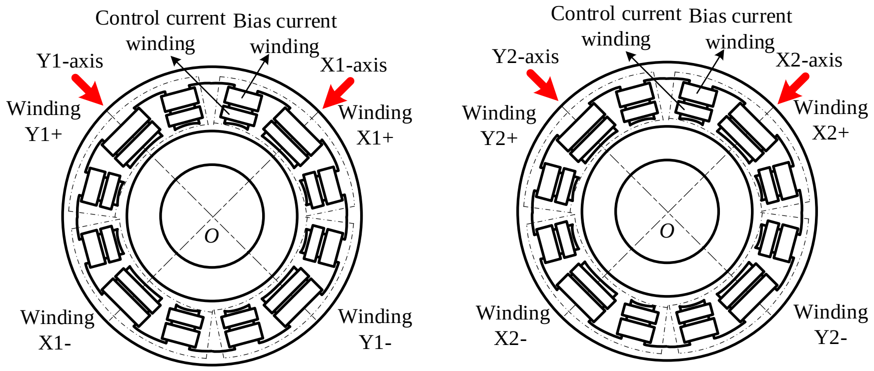
To solve this problem, scholars proposed a three-phase four-leg topology [4] and a five-phase six-leg topology [5]. The five-phase six-leg topology is shown in figure 1(a). The MB winding current is controlled by way of bridge leg multiplexing, which greatly reduces the cost. However, because the current stress carried by the common bridge leg results from the superposition of other bridge legs, the stress of the common bridge leg is too large, and the reliability and safety are reduced. Furthermore, [6] proposed a unipolar series-winding control topology to increase voltage utilization, ensuring better current control capability.



(a) (b)

Figure 1 Five-phase six-leg topology(a) and series-winding topology (b).

The series-winding topology proposed in this paper is shown in figure 1(b), which can realize the control of bipolar current and evenly distribute the current stress of the bridge legs. The theory analysis and control method of the series-winding topology are presented in Section 2. To verify the availability of the series-winding topology, the experiments are carried out on the AMB test rig in Section 3. Conclusions are summarized in Section 4.

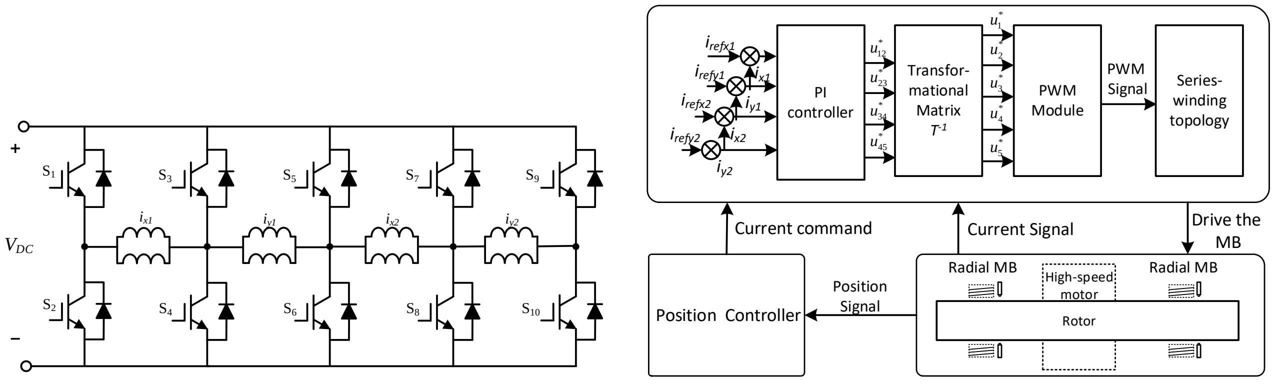


(a) (b)

Figure 2 Front end magnetic bearing(a) and rear end magnetic bearing (b).

Figure 2 shows the magnetic bearing test rigs' winding structure and pole distribution. The whole system obtains two radial magnetic bearings. The magnetic bearings are 12-pole radial magnetic bearings. Each side of one axis consists of three poles that stagger 45 degrees to provide electromagnetic force together. Both bias and control windings are on each side of the magnetic poles. All the bias windings are connected in series and supplied with a constant bias current from an additional source. To improve the response speed of the control winding current, two control windings opposite to each other on the same axis are connected in reverse parallel.

2. Control method of Series-winding topology



(a) (b)

Figure 3 Series-Winding topology(a) and overall diagram of the MB system (b).

As shown in figure 3, only the differential mode current component of the MB needs to be controlled. The upper and lower switching devices of each bridge leg are conducted complementarily. The switching mode $s_i = 1(i=1,2,3,4,5)$ is defined when the upper switching device is on and the lower switching device is off. Moreover, the upper switching device is off when the lower switching device is on, at which mode $s_i = 0$. So for each pair of control windings, the voltage modes at both ends include V_{DC}, 0, - V_{DC}. V_{DC} is the DC link voltage. It is easy to see that the current stress in the bridge legs at the two ends of the topology is the maximum value of the control current, and the current stress in the middle part of the bridge arm is up to twice the maximum value of the control current. Therefore, the current stress of the switching device is evenly distributed in each bridge leg compared to the common bridge leg structure.

Using pulse width modulated signals to drive switching devices. In the case of the average model, the voltage is controlled by the duty cycle of each switch device during a switching cycle. Variables d_1~d_5 represent the duty cycle of each bridge leg, and then the average voltages of each bridge leg midpoint u_1~u_5 are expressed as

$$\begin{bmatrix} u_1 & u_2 & u_3 & u_4 & u_5 \end{bmatrix}^T = \begin{bmatrix} d_1 & d_2 & d_3 & d_4 & d_5 \end{bmatrix}^T \times V_{DC} \tag{1}$$

In a control cycle, the relationship between the five winding currents i_{x1}, i_{y1}, i_{x2} and i_{y2}. The potentials u_1, u_2, u_3, u_4 and u_5 of each node are expressed in (2), where Z is the winding impedance.

$$i_{x1} = \frac{u_1 - u_2}{Z}, i_{y1} = \frac{u_2 - u_3}{Z}, i_{x2} = \frac{u_3 - u_4}{Z}, i_{y2} = \frac{u_4 - u_5}{Z} \tag{2}$$

Equation (2) can also be expressed in the form of a matrix

$$\begin{bmatrix} i_{x1} \\ i_{y1} \\ i_{x2} \\ i_{y2} \end{bmatrix} = \frac{1}{Z} \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} \tag{3}$$

To ensure that the potential at the midpoint of each phase leg is $0.5V_{\mathrm{DC}}$ in the steady state, it is limited in (4)

$$0.5V_{DC} = \frac{u_1 + u_2 + u_3 + u_4 + u_5}{5} \tag{4}$$

The duty cycle of each switch device is controlled according to the instruction value, and then the winding currents are adjusted. Equivalent voltage values across the windings between two bridge arms, the corresponding current times of the impedance *Z*, are used as instruction voltages. It means that u_{12}^* , u_{23}^* , u_{34}^* and u_{45}^* are the outputs of the PI controller. Superscript “ $*$ ” indicates that the parameter is the instruction value, and it is the per-unit value for the DC bus voltage V_{DC}. Let u_i^* indicates the midpoint voltage of the *i*th bridge leg. The potential voltage instructions of winding current instructions are obtained according to

$$\begin{bmatrix} u_{12}^* \\ u_{23}^* \\ u_{34}^* \\ u_{45}^* \\ 2.5 \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}}_{\boldsymbol{T}} \begin{bmatrix} u_1^* \\ u_2^* \\ u_3^* \\ u_4^* \\ u_5^* \end{bmatrix} \tag{5}$$

The transformation matrix in Equation (5) is denoted $\boldsymbol{T}$. By solving for the inverse matrix $\boldsymbol{T}^{-1}$ of $\boldsymbol{T}$, the transformation relationship from the PI command value to the control voltage of each bridge leg can be obtained, as shown in Equation (6)

$$\begin{bmatrix} u_1^* & u_2^* & u_3^* & u_4^* & u_5^* \end{bmatrix}^T = \boldsymbol{T}^{-1} \begin{bmatrix} u_{12}^* & u_{23}^* & u_{34}^* & u_{45}^* & 2.5 \end{bmatrix}^T \tag{6}$$

The control block diagram for the current loop is shown in figure 3(b). This work illustrates the four degrees of freedom of current control. But this method can also be extended to achieve N-degree-of-freedom current control.

3. Experiment

To verify the feasibility of this series-winding topology, the experiment is carried out under *V*dc=150V. The switching frequency is 20kHz. The specific parameters are shown in Table 1, and the experimental platform is shown in figure 5(a). The controller consists of two parts, the control board and the power board, which provide control commands and PWM signals and carry out current and position signal acquisition. The power board includes a power electronic topology and a drive circuit section to control the current after the windings are connected to the power board.

Table 1 Simulation Parameters

	Parameter	***Value***
g_0	Touch down bearing gap	200μm
s_0	AMB gap	400μm
I_0	Bias current	2 A
I_C	Control current	4A
f	Switching frequency	20kHz
*V*dc	DC-bus voltage	150 V

A given sinusoidal current command controls the four winding currents. The frequency and amplitude are 200Hz is 3A, respectively. The experiment results of four symmetrical sine waves with given signals are shown in figure 4. The current command value is given at 0.026 seconds. All four control currents track the command signal well.

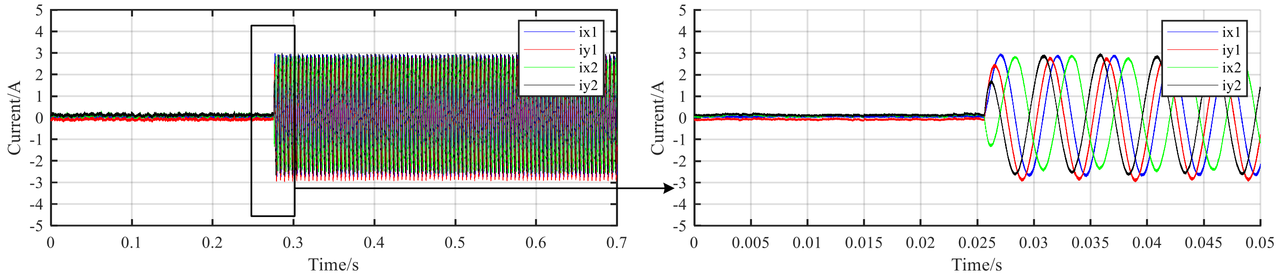
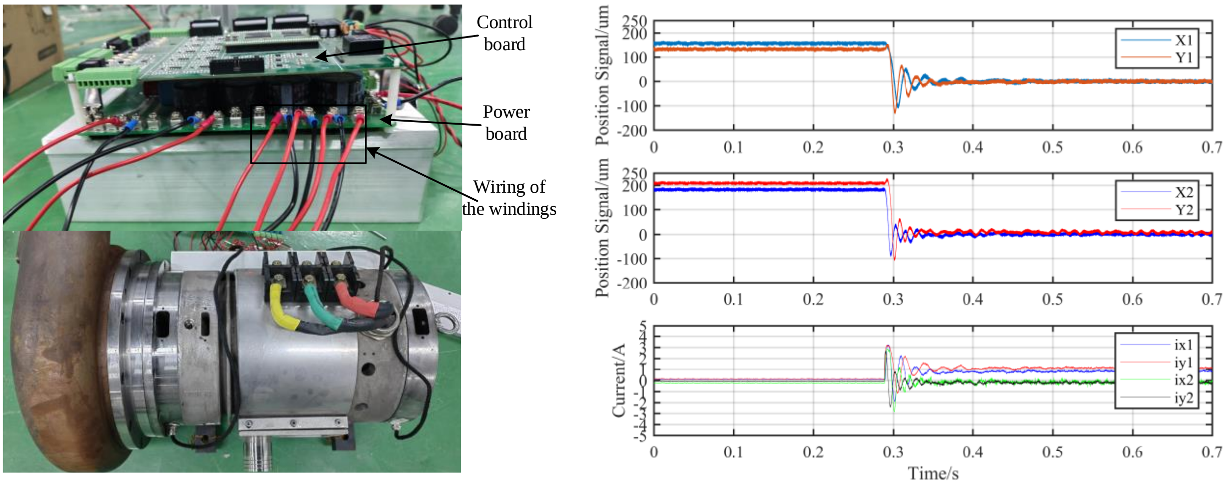


Figure 4 Current loop test results.

Suspension experimental tests were carried out on the experimental platform. Figure 5(b) shows the control winding current in four axes of magnetic bearing and the displacement of the rotor in the X1, Y1, X2 and Y2 axis. At first, the rotor leans against the touch-down bearing, then levitates to the center of the bearing. The suspension displacement fluctuations are controlled to within 20 µm.



(a) (b)

Figure 5 Series-Winding topology(a) and overall diagram of the MB system (b).

4. Conclusions

This article proposes a novel series-winding topology to drive four-axis MB. With only ten switching devices, this topology significantly decreases the switches and the current stress is evenly distributed. The series-winding topology can extend to N-degree of freedom MB systems for multi-axis control. The experiment shows that this scheme can realize the current control of MB well.

References

[1] Chiba, et al. (2005) Magnetic Bearings and Bearingless Drives. Elsevier Press.

[2] Xie, et al. (1999) Coil-wrapping of Electromagnetic Bearings and Forms of the Power Amplifier. Mechanical Science and Technology (04):103-104.

[3] Jiang, et al. (2020) Novel topologies of power electronics converter as active magnetic bearing drive. IEEE Transactions on Industrial Electronics 67(2): 950-959.

[4] Li, et al. (2011) Analysis and Simplification of Three-Dimensional Space Vector PWM for Three-Phase Four-Leg Inverters. IEEE Transactions on Industrial Electronics 58(2): 450-464.

[5] Fei, et al. (2012) A Control Strategy of Novel Five-phase Six-leg Switching Power Amplifiers Applied in Magnetic Levitating Bearing Systems. Journal of the Chinese Society of Electrical Engineering 32(09):124-131+19.

[6] Yang J, et al. (2021) Series-Winding Topology Converter for Active Magnetic Bearing Drive. IEEE Transactions on Industrial Electronics 68(12): 11772-11782.