Design and Application for Power Amplifier of Magnetic Bearing

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Abstract—Power Amplifier is a crucial part in the magnetic bearing control system, so the performance of power amplifier plays an important role in the magnetic bearing control system. According to the 5-DOF active magnetic bearing system, the half bridge structure which needs twenty power parts in total is generally used, with a bulky bearing controller. so this kind of power amplifier cannot be appropriate for the magnetic compressor who has a strict installation size require。 A novel kind of power amplifier is proposed which is based on the common lower bridge structure, with the ability of decreasing the amount of the power parts to 15 and cutting down the volume of bearing controller. The simulation and test shows that the common lower bridge has a good response of capability and actual performance.

I. INTRODUCTION

The power amplifier is responsible for converting the given signal of the controller into the current signal in the electromagnetic winding, thereby generating the electromagnetic force acting on the rotor. Through the continuous adjustment of the control system, the stable suspension of the rotor is finally achieved. The power amplifier is necessary for the magnetic suspension bearing control system[1].

The rotor of the magnetic suspension bearing requires a control force to be exerted on each of five degrees of freedom to achieve complete suspension, namely, the front and rear two radial magnetic bearings and one axial magnetic bearing are required. The active magnetic bearing system uses a differential control method, which requires a total of 10 bearing windings for the five degrees of freedom. Therefore, the five-degree-of-freedom magnetic bearing system generally requires 10 independent switching power amplifiers. The bearing controller hardware needs a large volume and a large number of power devices to realize, while the magnetic suspension centrifugal compressor has relatively high requirements for the heat dissipation and installation volume of the bearing controller. The volume of the magnetic suspension bearing power amplifier directly affects the volume of the magnetic suspension bearing controller, so it is necessary to carry out the research of new switching power amplifier.

In this paper, a new power amplifier design method is proposed, the windings sharing the structure of the lower arm. Three switching devices and three diodes can control two bearing windings, which are applied in a magnetic levitation refrigeration centrifugal compressor. The simulation and actual results verify that the program has a high practicality.

II. POWER AMPLIFIER TOPOLOGY AND WORKING PRINCIPLE

A. Conventional structure and working principle

The power amplifiers used in magnetic bearings include linear power amplifiers and switching power amplifiers. In order to reduce the switching losses and current ripple in the bearing windings, the active magnetic bearing control system uses a three-level PWM switching power amplifier.

In a three-level power amplifier, the PWM generator generates two different PWM drive signals based on the result of the PI regulator, and triggers the upper and lower arms in the power amplifier respectively. The power amplifier adjusts the duty cycle of the PWM drive signal based on the reference signal, thereby controlling the magnitude of the current in the bearing windings.

In the active magnetic suspension bearing control system, the control current does not need to change the flow direction, so the switching power amplifier generally adopts a H half-bridge topology [2], as shown in Figure1.

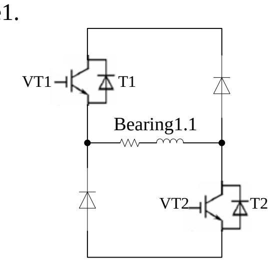

Figure 1. H half-bridge topology

VT1 and VT2 are the PWM drive signals of the upper and lower arm of the power amplifier. When the duty cycle of VT1 and VT2 is greater than 50%, the winding current increases when the upper and lower arm are simultaneously turned on; when the duty cycle of VT1 and VT2 duty cycle is equal to 50%, the winding current continues to flow through the diode and remains unchanged; When the duty cycle of VT1 and VT2 is less than 50%, the two diodes in the main circuit are turned on simultaneously when the upper and lower arm are turned off at the same time, the current in the winding is reduced[3]. The PWM drive and current waveform of the bearing winding are shown in Figure 2.

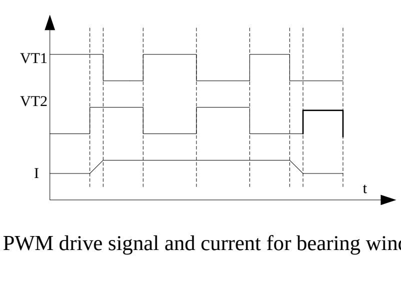

Figure 2. PWM drive signal and current for bearing winding

The mutual conversion of these states causes the current in the winding to increase, decrease, or continue to follow given reference signal of the controller.

Each H-bridge circuit controls one bearing winding. Therefore, an active magnetic bearing control system requires 10 independent H-bridges, that is, 20 power switching devices and 20 diodes are required. The amount of power devices will result in higher hardware costs and larger hardware volume, which will become the key factors that restrict the development of magnetic bearings.

B. Proposed new power amplifier

In order to reduce hardware costs and the volume of the bearing controller, making the magnetic bearing controller meets the special requirements of the centrifugal compressor, a new type of power amplifier structure is proposed. Two differential control windings in one direction share a 50% fixed duty cycle for lower arm. Three power switching devices and three diodes can control two bearing windings. Therefore, the switching power amplifier of the entire magnetic suspension control system requires only 15 switching power devices and 15 diodes, reducing the number of power devices used by 1/4. The volume of the bearing controller is reduced to meet the requirements of the centrifugal compressor. The specific structure is shown in Figure 3.

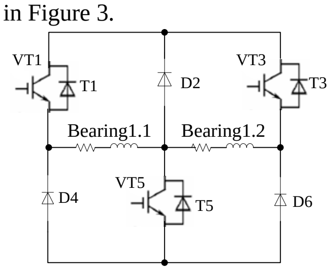

Figure 3. Proposed three-arm power amplifier structure

For example, in the radial bearing X-direction control winding, X1 and X2 windings share the switching power device T5, and the duty cycle of T5 is fixed at 50%.

In the active magnetic suspension bearing control system, the outer ring is the displacement control and the inner is the current control, as shown in Figure 4. Reference position and feedback position generates a current control signal i_c through the role of the displacement regulator, the reference current of X1 winding is $I_0 - i_c$, the reference current of X2 winding is $I_0 + i_c$.

When the rotor reference position is greater than the feedback position, the error and the control current is greater than zero, the reference current of X2 winding increases and the one of X1 winding decreases. At this time, the duty cycle of T1 should be less than 50% and the one of T3 should be greater than 50%. The electromagnetic force generated by X2 winding will be greater than the force generated by X1 winding, the rotor is adjusted back to the reference position. Conversely, when the rotor reference position is less than the feedback position, the duty cycle of T1 should be greater than 50% and the one of T3 should be less than 50%. T5 is the common lower arm, so the current flowing through T5 is $2 * I_0$.

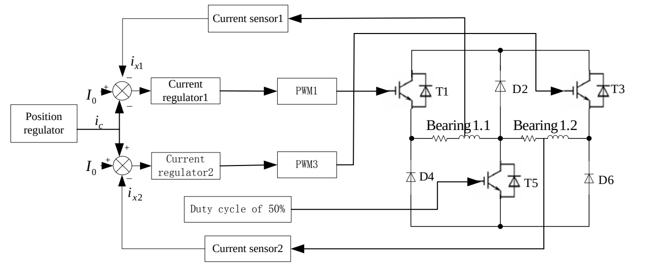

Figure 4. New power amplifier in magnetic levitation control system

Switching power amplifier itself is a tracking control circuit, the goal is to make the actual current output follow the input control signal without distorting. According to the different comparisons results of the control and the actual current signal, increase or decrease the load current by turning on or off the power supply.

The relationship between the voltage and current of the electromagnet coil can be expressed as[4]:

$$U = L\frac{di}{dt} + iR + \Delta U \tag{1}$$

In the formula, the input DC voltage is U, and the equivalent resistance and inductance of the electromagnetic bearing coil are R and L respectively, and the current of the electromagnetic winding is i, ΔU is the pressure drop of other links. ΔU and iR are comparatively small and negligible, so the maximum rate of change of current is:

$$\frac{di}{dt}\Big|_{\max} = \frac{U}{L} \tag{2}$$

Equation (2) shows that the current response speed depends on the coil inductance L and DC bus voltage U.

For a sinusoidal current $i = i_a \sin(\omega t)$:

$$\frac{di}{dt}\Big|_{\max} = i_a \omega \cos(\omega t) \le i_a \omega \le \frac{U}{L} \tag{3}$$

When equation (3) is established, it can be approximately considered that the power amplifier can give a corresponding response current without distortion. Assuming that the inductance is not changed, increasing the DC bus voltage will speed up the response speed of the output current of the power amplifier.

III. SIMULATION

In order to verify whether the new power amplifier can meet the requirements of the application, a simulation model of the magnetic suspension bearing current control was set up in the MATLAB/SIMULINK environment. The simulation of the new power amplifier design was verified. The simulation model is shown in Figure 5.

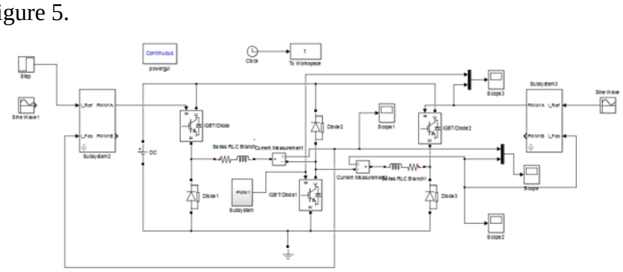

Figure 5. Application of new power amplifier in magnetic levitation system

Inductance and resistance of X1 and X2 winding are the same, and the same DC bus voltage is used to supply X1 and X2 winding.

Step, sine and abrupt reference current signals are put in use in the simulation to verify whether the closed loop control current of the X1 and X2 windings in the novel power amplifier will influence each other because of the community arms.

A. Step response

At 0.3s, the amplitude of the step input signal of X1 winding changes from 0 to 1. At 0.2 s, the step input signal amplitude of X2 winding changes from 1 to 0, and the output current response of X1 and X2 windings is observed.

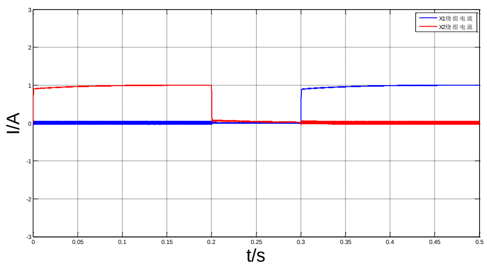

Figure 6. Step response of X1 and X2 windings during current closed-loop control

As can be seen from Figure 6, in the current closed-loop control, the output current of X1 and X2 winding can correctly respond to the input step signal and quickly track the given reference current, X1 and X2 windings do not interfere with each other.

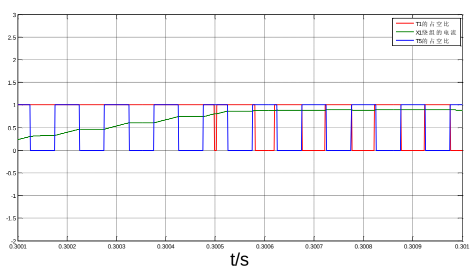

Figure 7. The duty cycle and current relationship of the X1 windings as the current increases

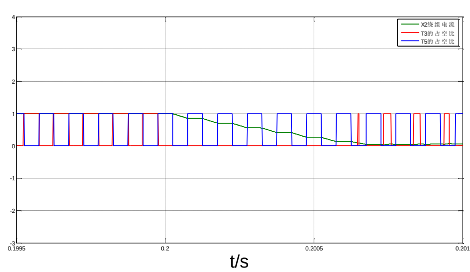

Figure 8. The duty cycle and current relationship of the X2 windings as the current decreases

The reference current of X1 and X2 windings are respectively rising and falling. Based on the respective current regulators, the generated PWM duty cycle of the switching devices T1 and T3 can control the current changes of X1 and X2 windings, as shown in Figure 7 and Figure 8, the simulation results are unified with the theoretical analysis.

B. Sinusoidal current response

With the same inductance and resistance, the same DC bus voltage supply, giving the amplitude of 1, the frequency of 10Hz sine reference current to X1 winding, the amplitude of 1, the frequency of 50Hz sine reference current to X2 winding, observing the output current response of X1 and X2 winding.

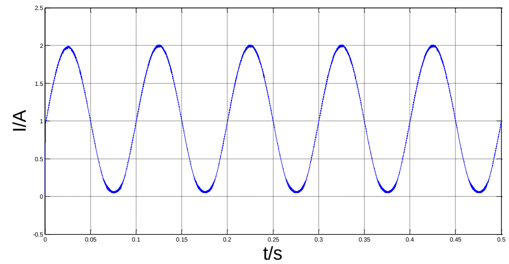

Figure 9. Sinusoidal response at 10Hz for X1 winding

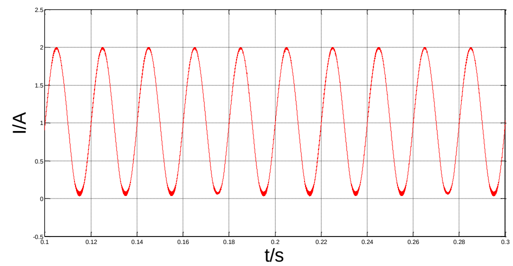

Figure 10. Sinusoidal response at 50Hz for X2 winding

It can be seen from Figure 9 and Figure 10 that under the condition that the amplitude of the sinusoidal current is relatively small and the frequency is relatively low, the output current of X1 and X2 winding can follow the given sinusoidal reference current without distortion and phase lag. It can be a good response to sinusoidal input signal.

Magnetic suspension centrifugal compressor refrigeration systems often run at high speeds and speeds up to a few hundred hertz. To verify the dynamic response of a new power amplifier under high frequency signals, a 500 Hz sinusoidal input signal is given to X2 winding, observing the output current response of X2 winding.

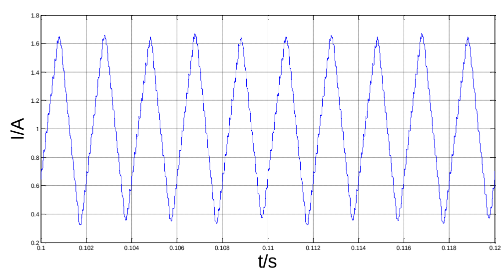

Figure 11. Sine response at 500Hz for X2 winding

It can be seen from Figure 11 that after increasing the given sinusoidal current frequency to 500Hz, the output current of the bearing winding is distorted, which does not accurately reflect the changing trend of the given reference current. The current response speed cannot meet the requirements of the control system. Based on the above theoretical analysis, we will verify the effect of increasing the bus voltage on the current response speed of the bearing winding.

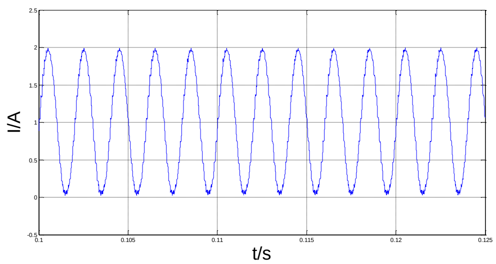

Figure 12. Sinusoidal response at 500Hz for X2 winding by increasing bus voltage

It can be seen from Figure 12 that after raising DC bus voltage, the output current of X2 winding recovers the following capability, which can meet the needs of the magnetic suspension bearing control system at high frequencies.

C. Mutation response

In order to analyze the effect of the decoupled control characteristics of the common bridge arm on the 2-winding current, step current signal is given as a sudden signal change to X1 winding, at the same time the sinusoidal current signal is given to X2 winding. The impact on sudden change of current of X1 winding to that of X2 winding is simulated and analyzed.

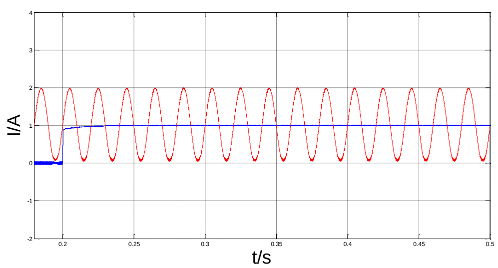

Figure 13. The effect of abrupt change of current of X1 winding on the output current of X2 winding

It can be seen from Figure 13 that when the current of X1 winding is suddenly changed, the output current of X2 winding can still accurately track the given current. No phenomenon shows that the control signal missed due to the sudden change in the current of X1 winding. Therefore, there is no coupling effect between the windings in the new power amplifier.

IV. EXPERIMENTAL VERIFICATION

In order to further verify the correctness of the above simulation and theoretical analysis, the dynamic response of the new power amplifier is studied in an actual circuit, the application of new power amplifier in the magnetic levitation centrifuge is shown in Figure 14.

Figure 14. Application of new power amplifier in the magnetic levitation centrifuge

A. Step response experiment

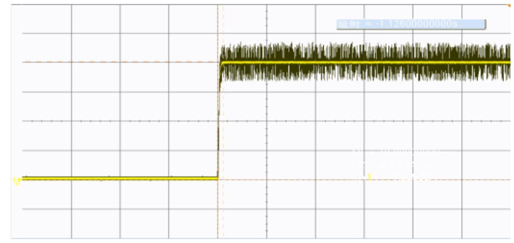

Figure 15. Experiment result of step response

Observing the actual output current of the winding with an oscilloscope, as shown in Figure 15. The output current of the winding can correctly respond to the given reference signal.

B. Sinusoidal current response experiment

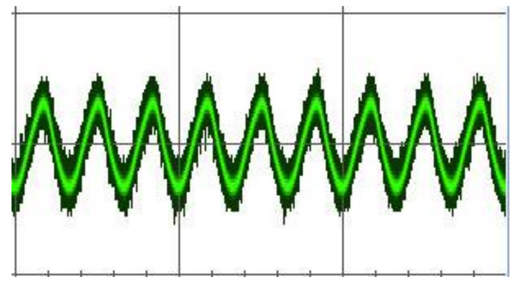

Figure 16. Experiment result of sinusoidal response

Observing the actual output current of the winding with an oscilloscope, as shown in Figure 16. The output current of the winding can correctly respond to the given reference signal.

V. CONCLUSION

This paper presents a new design of switching power amplifiers. The method of using the windings to share the lower arm makes it possible to use 3 power devices and 3 diodes to control the 2 windings of the differential signal and reduce the use of 1/4 power devices, saving hardware costs, while reducing the size of the magnetic bearing controller. It has been successfully applied in the refrigeration centrifugal compressor with a high practical value.

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