Realization of Magnetic Suspension and Motor Operation with One Three-phase Voltage Source Inverter Using a Zero-Phase Current

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***Abstract*—This paper focuses on realization of both the single-axis active magnetic suspension and rotation of a three-phase permanent magnet motor using only one three-phase voltage source inverter. The suspension winding of the electromagnet for the single-axis magnetic suspension is connected between the neutral point of the Y-connected three-phase winding and the middle point of the voltage sources, and the resulting zero-phase current is utilized to control the suspension force. The control method of the zero-phase current is theoretically derived to avoid interference with the motor performance. Experimental apparatus was built and tested, which consists of an iron ball magnetic suspension system and a three-phase interior permanent magnet motor. The experimental results demonstrated stable magnetic suspension and motor rotation at 1200 rpm.**

I. INTRODUCTION

Conventional five-axis actively regulated bearingless motors and magnetic bearings require a number of electromagnets, displacement sensors, and inverters [1, 2]. To reduce the size, cost, and power consumption, one-axis actively positioned magnetic bearings have been previously developed [3, 4]. These machines generally combine both a thrust magnetic bearing for axial suspension and a motor for rotation. The remaining two-translational and two-tilting motions of the rotor are passively stabilized. In these machines, at least two inverters are needed to regulate the suspension and motor currents independently.

A one-axis actively positioned bearingless motor has been previously proposed [5]. This bearingless motor has unique rotor structure and winding configuration using four coreless coils to generate both axial suspension force and torque. In this bearingless motor, two independent currents are regulated to control the torque and axial suspension force. The radial and tilting motions of the rotor are passively stabilized by the repulsive type permanent magnet (PM) pairs. The authors have previously developed one-axis actively positioned bearingless motor using only one three-phase inverter, dubbed a single-drive bearingless motor [6]. Magnetic couplings between the rotor and the stator stabilize the radial and tilting motions of the rotor passively. The axial position and torque are stabilized by regulating the *d*- and *q*-axis currents, respectively. However, only two independent *d*- and *q*-axis currents are actively regulated by one three-phase inverter. If three-axis currents are independently regulated by only one three-phase inverter, further cost reduction, downsizing, and energy saving for the magnetically suspended machines can be achieved.

This paper focuses on realization of both the single-axis active magnetic suspension and rotation of a PM motor using only one three-phase voltage source inverter. The final goal of this study is to apply the proposed control method to a one-axis actively regulated bearingless machine, which consists of, for instance, a PM motor, repulsive type passive magnetic bearings for non-contact shaft suspension in the radial and tilting directions, and a thrust magnetic bearing. In this paper, we propose a novel concept that the suspension winding is connected between a neutral point of the Y-connected three-phase winding and a middle point of the voltage sources, and resulting zero-phase current generates the suspension force. To our knowledge, application of the zero-phase current to active actuator control is new to the field of magnetic bearings, bearingless motors, and electric machines and drives.

In section II, the proposed control method to avoid interference of the zero-phase current with motor performance is theoretically derived. Section III presents results of circuit simulation using a commercially available circuit simulator. To verify the proposed control method, we fabricated the experimental apparatus which consists of a three-phase interior permanent magnet (IPM) motor and a single active magnetic suspension system with an iron ball. The experimental results with this test machine are shown in Section IV.

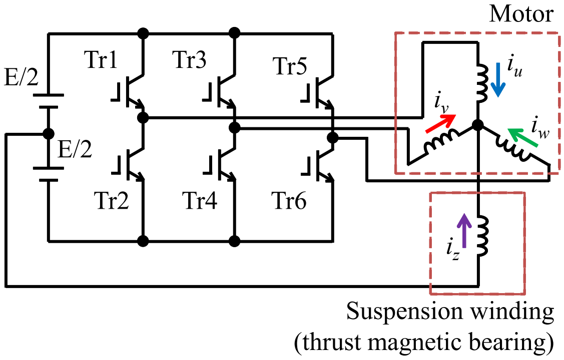

Figure 1. Circuit configuration of the proposed control method.

II. CONTROL METHOD OF ZERO-PHASE CURRENT

Figure 1 shows a circuit configuration of the proposed control method. The suspension winding is connected between a neutral point of the Y-connected three-phase winding and a middle point of the voltage sources, and resulting zero-phase current i_z generates the suspension force. For example, when the all lower transistors, Tr2, Tr4, and Tr6, are turned off and Tr1, Tr3, and/or Tr5 are turned on, a zero-phase current i_z flows through the suspension winding from the neutral point to the voltage middle point. In this section, the control method of this zero-phase current to avoid influence on motor performance is theoretically introduced.

The transformation of the three-phase (I_u, I_v, I_w) frame into the zero-direct-quadrature (I_0, I_d, I_q) frame is given by

$$\begin{bmatrix} \dot{I}_0 \\ \dot{I}_d \\ \dot{I}_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{4\pi}{3}) \\ -\sin\omega t & \sin(\omega t + \frac{\pi}{3}) & \sin(\omega t - \frac{\pi}{3}) \end{bmatrix} \begin{bmatrix} \dot{I}_u \\ \dot{I}_v \\ \dot{I}_w \end{bmatrix} \tag{1}$$

where ω ant t are the angular frequency and time, respectively. In a general motor, three-phase current vector is given by

$$\begin{bmatrix} \dot{I}_u \\ \dot{I}_v \\ \dot{I}_w \end{bmatrix} = \sqrt{2} I_e \begin{bmatrix} e^{j(\omega t+\theta)} \\ e^{j(\omega t+\theta-2\pi/3)} \\ e^{j(\omega t+\theta-4\pi/3)} \end{bmatrix} \tag{2}$$

Substituting (2) into (1) yields

$$\begin{bmatrix} \dot{I}_0 \\ \dot{I}_d \\ \dot{I}_q \end{bmatrix} = \sqrt{3} I_e \begin{bmatrix} 0 \\ e^{j\theta} \\ -je^{j\theta} \end{bmatrix} \tag{3}$$

where I_e and θ are the root-mean-square value and phase of the current, respectively. It can be observed that the zero-phase component is always zero and d- and q- components are dc values and not a function of time.

On the other hand, to feed the zero-phase current actively into the suspension winding, dc components (I_{u0}, I_{v0}, I_{w0}) have to be added to each phase current, which can be written as,

$$\begin{bmatrix} \dot{I}_u \\ \dot{I}_v \\ \dot{I}_w \end{bmatrix} = \sqrt{2} I_e \begin{bmatrix} e^{j(\omega t+\theta)} \\ e^{j(\omega t+\theta-2\pi/3)} \\ e^{j(\omega t+\theta-4\pi/3)} \end{bmatrix} + \begin{bmatrix} I_{u0} \\ I_{v0} \\ I_{w0} \end{bmatrix} \tag{4}$$

Substituting (4) into (1) yields

$$\begin{bmatrix} \dot{I}_0 \\ \dot{I}_d \\ \dot{I}_q \end{bmatrix} = \begin{bmatrix} \dfrac{(I_{u0}+I_{v0}+I_{w0})}{\sqrt{3}} \\ \sqrt{3} I_e e^{j\theta} + \dfrac{(2I_{u0}-I_{v0}-I_{w0})\cos\omega t}{\sqrt{6}} + \dfrac{(I_{v0}-I_{w0})\sin\omega t}{\sqrt{2}} \\ -\sqrt{3} I_e je^{j\theta} - \dfrac{(2I_{u0}-I_{v0}-I_{w0})\sin\omega t}{\sqrt{6}} + \dfrac{(I_{v0}-I_{w0})\cos\omega t}{\sqrt{2}} \end{bmatrix} \tag{5}$$

To obtain time-independent dc values of I_d, I_q, the following conditions should be satisfied, as,

$$\begin{aligned} 2I_{u0} - I_{v0} - I_{w0} &= 0 \\ I_{v0} - I_{w0} &= 0 \end{aligned} \tag{6}$$

This results in the following using a dc component, I_z, as,

$$I_{u0} = I_{v0} = I_{w0} = I_z \tag{7}$$

Substituting (7) into (5) yields

$$\begin{bmatrix} \dot{I}_0 \\ \dot{I}_d \\ \dot{I}_q \end{bmatrix} = \sqrt{3} \begin{bmatrix} I_z \\ I_e e^{j\theta} \\ -I_e je^{j\theta} \end{bmatrix} \tag{8}$$

Therefore, the equivalent dc components should be fed into the three-phase currents to have no influence on the motor performance.

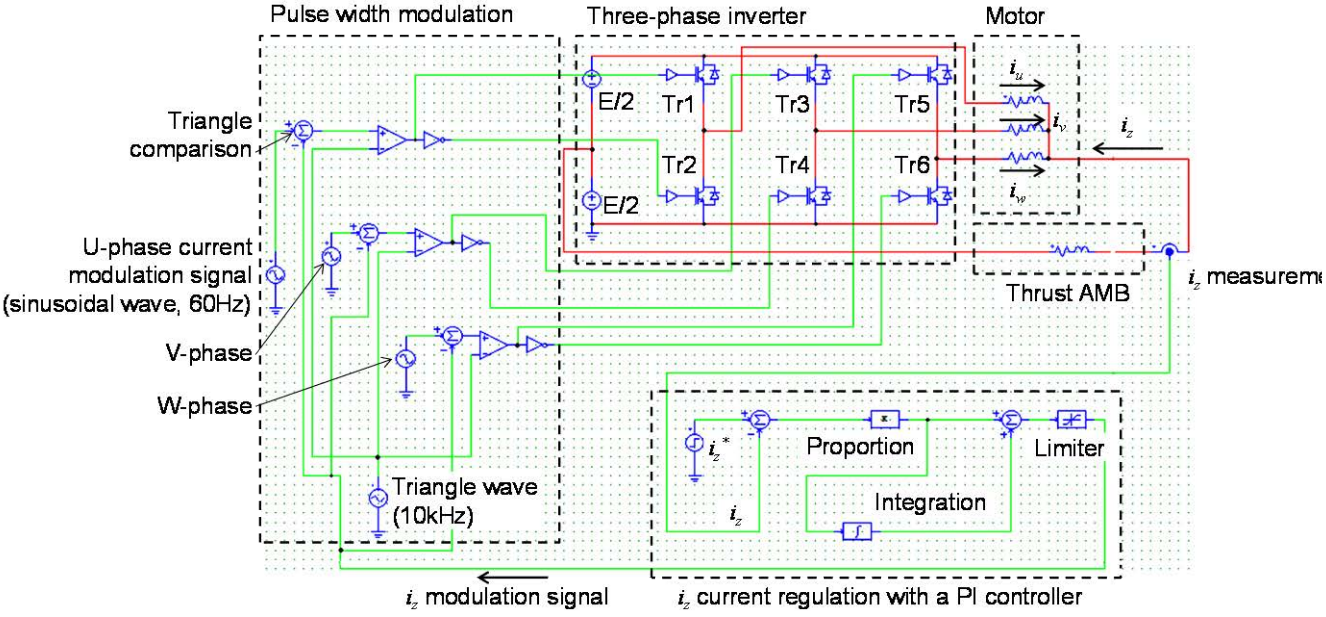

Figure 2. Circuit configuration of the proposed control method.

III. CIRCUIT SIMULATION

Circuit simulation is performed using a commercially available software (PSIM, Myway Plus Corp., Japan). Figure 2 shows simulation blocks using the pulse-width-modulation (PWM) voltage source inverter. A triangle wave generator with a carrier frequency of 10 kHz and a comparator generate PWM signals. Three-phase open-loop alternating currents with a frequency of 60 Hz are provided to the motor windings. To simplify the control circuit, all windings of the three-phase motor and magnetic bearing consist of resistance and inductance. The induced voltage of the motor is not considered in this simulation. A zero-phase current is measured and regulated by proportional-integral (PI) controller. This PI controller outputs a modulation component, which is then equally added to each phase.

Figure 3 shows the simulation result of the zero-phase current control. Three-phase currents and zero-phase current are shown in top and bottom graphs, respectively. The zero-phase current control is activated after 0.1 s to feed 3 A into the suspension winding. A dc component of 1 A is fed into each phase of the motor winding. As can be seen, the zero-phase current rises within 10 ms. The simulation results demonstrated that the zero-phase current was controlled by adding a desired dc component to the PWM modulation signal of the three-phase inverter.

IV. EXPERIMENT

To verify the proposed method, we built an experimental apparatus which consists of a three-phase IPM motor and a single magnetic suspension system with an iron ball. Figure 4 shows a schematic of the control diagram. The suspension winding of the electromagnet is connected between the neutral point of the Y-connected three-phase motor winding and the middle point of the voltage source. An axial motion of the iron ball, z, is detected by an eddy current type displacement sensor. A proportional-integral-derivative (PID) controller outputs the zero-phase current reference, i_z*, and stables motion of the iron ball. Based on (1), the references of d-axis, q-axis, and zero-phase currents, i_d*, i_q*, and i_z* are transformed into the three-phase current references, i_u*, i_v*, and i_w*. Because of the Y-connected winding configuration, the three-phase current, i_u, i_v, and i_w, and zero-phase current, i_z, have the following relationship due to Kirchhoff's current law, as,

$$I_u + I_v + I_w + I_z = 0 \tag{9}$$

Three of those currents are independent variables. Therefore, three-phase currents are detected and actively regulated by the PI controller.

Figure 5 shows a picture of the experimental apparatus. The electromagnet for the single-axis magnetic suspension does not include any PMs. A hollow iron ball with a diameter of 50 mm and a weight of 160 g is used. A bias current of the electromagnet for magnetic suspension of the iron ball is set to be 1 A. A three-phase four-pole/six-slot IPM motor with a rated power of 1.5 kW is driven under no load condition. The d-axis current reference, i_d*, is set to 0 A. Two power supplies (ZX-400L, Takasago Ltd., Japan) with a dc voltage of 30 V each are used and thus the dc link voltage of the inverter is 60 V. A custom-made inverter equipped with an intelligent power module (PS21353-N, Mitsubishi Electric Corp., Japan) and a real-time digital controller (Nc-RIO-9022, National Instruments Corp., USA) is used. A carrier frequency of the PWM is 10 kHz.

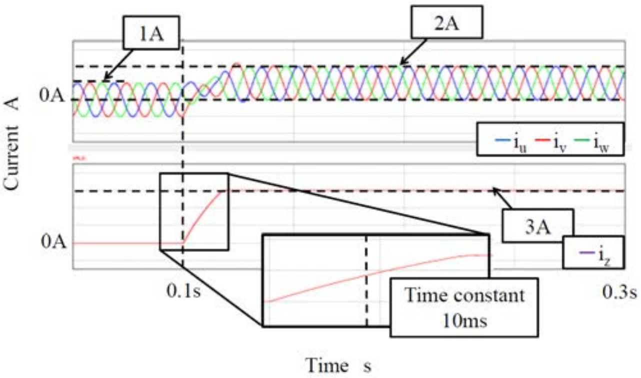

Figure 3. Simulation results of the zero-phase current control.

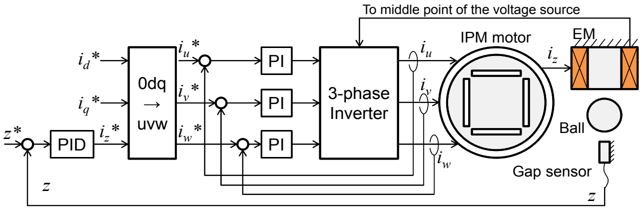

Figure 4. Schematic of the control diagram.

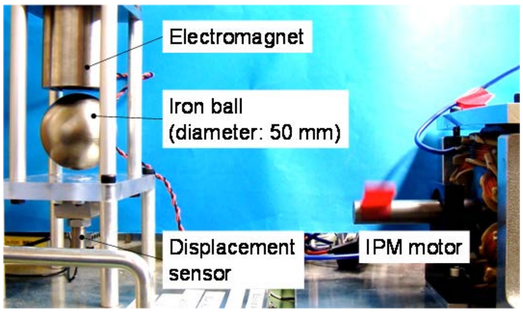

Figure 5. Experimental setup.

The PID controller parameters for magnetic suspension were independently regulated and then the iron ball was successfully levitated. Figure 6 shows the U-phase current, i_u, the zero-phase current, i_z, and the axial displacement of the iron ball, z, when the magnetic suspension control is activated at a rotational speed of 1200 rpm. The zero-phase current increased rapidly to pull up the iron ball although undesirable current fluctuation occurred partially. After 0.2 s, the axial displacement, z, reached reference value of 5 mm. Figure 7 shows the three-phase currents, the zero-phase current, and the axial displacement in steady-state at 1200 rpm. The iron ball was stably suspended with the zero-phase current regulation. The vibration amplitude of the iron ball in the axial direction was 60 μm (3σ). Although the three-phase ac currents are flowing, the dc component in W-phase does not correspond with those of U-phase and V-phase. In future works, we will address an evaluation of the motor performance with magnetic suspension condition, a further investigation of interference between the magnetic suspension and motor drive, and a non-contact IPM motor drive using only one three-phase inverter.

V. CONCLUSION

This paper describes a novel concept that two independent motor currents, i_d and i_q, and one suspension current, i_z, are independently controlled using only one three-phase voltage source inverter. The zero-phase current that corresponds to the suspension current, i_z, is utilized to actively regulate the suspension force. A control method of this zero-phase current was theoretically derived to avoid an influence on the motor performance. Experimental results demonstrated active regulation of the zero-phase current and successful magnetic suspension during motor rotation at 1200 rpm using only one three-phase inverter.

ACKNOWLEDGMENT

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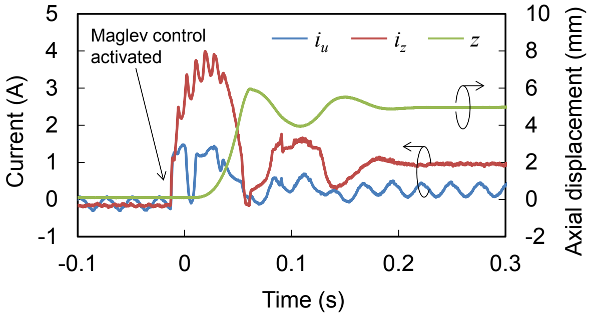

Figure 6. Measured U-phase current, zero-phase current, and axial displacement of the iron ball when magnetic suspension is activated at a motor speed of 1200 rpm.

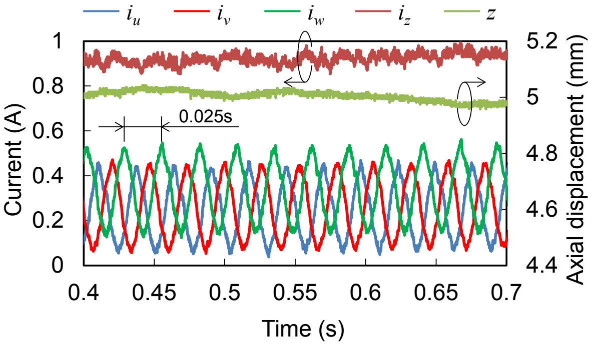

Figure 7. Measured three-phase current, zero-phase current, and axial displacement of the iron ball in steady-state at 1200 rpm.

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