Multisource Oscillation Suppression Control of Magnetic Levitation High Speed Permanent Magnet Motor

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Abstract

The multi-source oscillation of magnetic levitation permanent magnet motor (ML-PMM) under high speed operation is inevitable. The reasons are the influence of the strong coupling characteristics of high speed permanent magnet motor (HSPMM), the nonlinear characteristics of power converter and the coupling characteristics of magnetic levitation control system. Aiming at the multi-source oscillation caused by magnetic levitation system and HSPMM, the multi-source oscillation suppression control method suitable for magnetic levitation-high speed permanent magnet motor (ML-HSPMM) is studied in this paper. The stability of ML-HSPMM and the small signal model of the motor are analyzed. Finally, the control strategy is verified by simulation and experiment.

Index Terms

Magnetic levitation, high speed permanent magnet motor, oscillation, suppression control.

I. INTRODUCTION

With high power density and unique structure, magnetic levitation high speed permanent magnet motor (ML-HSPMM) has attracted more and more attention and research [1]. ML-HSPMM includes magnetic levitation system and high-speed permanent magnet motor (HSPMM), which has good application prospects in the fields of centrifugal blower, flywheel energy storage system and distributed generation. The reliable operation of ML-HSPMM includes the dependable operation of magnetic levitation system and permanent magnet motor (PMM) under high speed rotating magnetic field [2], [3].

Active magnetic bearing (AMB) is an important part of ML-HSPMM, of which principle is that the rotor is levitated in suspension without contacting the stator by using electromagnetic force. In present, many methods were used to suppress the unbalanced vibration. The self-balancing algorithm based on adaptive stress was proposed to reduce the synchronous unbalance vibration of the rotor system to almost zero [4]. The recursive method to suppress unbalance vibration of AMBs rigid rotor system was presented to compensate the unbalance vibration of the rotor [5]. The variable step size real-time iterative seeking algorithm was proposed to reduce the rotor’s vibration to a large extent [6]. A method based on the polarity switching tracking filter is proposed to achieve vibration suppression of the rigid rotor system on AMBs supported high-speed motors in the full rotational speed range [7].

In recent years, several modern control algorithms have been applied to obtain improved performance of motor. The robust oscillation controller was proposed to suppress the oscillation and improve the performance for integrated motor transmission [8]. In particular, the inner current loop in the field oriented control affects the dynamic and steady performance of permanent magnet motor. To avoid torque oscillations and overshoots during rapid speed variation, an improved model predictive direct speed control was
proposed in [9]. A rotor field-oriented V/f drive implementation was presented, and an oscillation suppression compensator was added to improve the system’s dynamic performance for both steady and transient states [10]. A feedback control strategy for mitigating pressure oscillations in centrifugal pumping systems was proposed, which modulated the rotational speed setpoint of the centrifugal pump rotor to produce an extra damping torque [11]. The mechanism of rotation frequency oscillations suppression strategy was analysed, and a strategy using active control of stator current was proposed to suppress the rotation-frequency oscillations in PMSM traction system [12]. A controller using sine wave transfer functions to reduce the rotational speed pulsation was proposed when the rotational speed of the motors is fluctuated and the drive system is vibrated due to the pulsating load torque [13]. Aiming at the DC-link voltage fluctuation caused by reducing the capacitance, a voltage fluctuation suppression strategy was proposed, which could adopt the sampled DC-link voltage to control the motor to suppress the power fluctuation on DC-link [14]. A precise calculation method for estimating the frequencies and amplitudes of dual-PWM adjustable speed drives input interharmonic due to torque oscillations is provided [15].

The difficulties of this paper include the oscillation control of magnetic levitation system and the high-speed operation control of permanent magnet motor. Firstly, the oscillation mechanism and the stability analysis of ML-HSPMM by the small signal model are analyzed. Secondly, the stability of ML-HSPMM is further analyzed, and the small signal model of the motor is deduced. The control strategy is studied, which is verified by simulation and experiment.

II. CAUSE ANALYSIS

The topology of ML-HSPMM based on pulse width modulation (PWM) converter is shown in Fig.1. The voltage and current of DC side are \( u_{dc} \) and \( i_{dc} \) respectively. The capacitance of DC side is \( C_{dc} \). The three-phase currents of ML-HSPMM are \( i_a, i_b, i_c \). The three-phase voltages of PWM converter are \( u_a, u_b, u_c \) respectively. The magnetic bearing control system includes power amplifier, rotor system, position controller, etc. Two electromagnets generate a pair of opposite acting forces when the differential control mode is adopted. When the rotor’s gravity is in balance with the electromagnetic force, the rotor can be stabilized at a certain equilibrium position.

The main factors causing oscillation of ML-HSPMM include:

1. The nonlinear characteristics of ML-HSPMM and power converter are easy to cause motor oscillation under high-speed operation state.

2. The magnetic levitation system consists of bearing, displacement sensor, power amplifier, position controller, magnetic and rotor. The mutual coupling of displacement sensors and the magnetic bearing are easy to cause the vibration of magnetic levitation system, which can cause the oscillation of motor.

3. ML-HSPMM is very sensitive to signal sampling delay, filter delay, switching delay and dead time under high frequency operation, which is easy to cause current oscillation of motor.

4. The imbalance of energy exchange between DC side of power converter and AC side of ML-HSPMM at high fundamental frequency and high carrier frequency, which is easy to cause system instability and motor oscillation.

5. The DC side fluctuation of the power converter superimposes the harmonic of the inverter output component, resulting in high frequency torque ripple and motor oscillation.

![FIGURE 1. Topology of ML-HSPMM.](image-url)
of which transfer function $G_{PI3}(s)$ is used to realize the speed of HSPMM at the same time. In addition, the mode.

where, $k_d$ is the proportional coefficient of $d$-axis current regulator, $\tau_{id}$ is the lead time constant of $d$-axis current regulator.

The expression of $d$-axis voltage command $u_d^*$ is shown in Eq.(3).

$$u_d^* = G_{PI3}(s)(i_d^* - i_d) - \omega_k L_q i_q$$

The expression of $q$-axis voltage command $u_q^*$ is shown in Eq.(4).

$$u_q^* = G_{PI2}(s)(i_q^* - i_q) + \omega_k (L_d i_d + \psi_t)$$

where, $i_d^*$ and $i_q^*$ are the current output by the speed loop, $i_d$ and $i_q$ are $dq$ axis components of stator current respectively, $\omega_k$ is the electrical angular velocity, $L_d$ is the $d$-axis inductance component, $\psi_t$ is the flux linkage of motor.

The stability of ML-HSPMM is further analyzed, and the small signal model of the motor is deduced. In $dq$ coordinate system, the relationship among in $d$-axis voltage $u_d$, $q$-axis voltage $u_q$, phase voltage $u_s$, phase angle $\gamma$ of motor is shown in Eq.(5).

$$\begin{align*}
    u_d &= u_s \cos \gamma \\
    u_q &= u_s \sin \gamma
\end{align*}$$

When the speed of ML-HSPMM is running at the rated speed, the expressions of steady-state values $u_{d0}$ and $u_{q0}$ of $d$-axis and $q$-axis voltage are shown in Eq.(6).

$$\begin{align*}
    u_{d0} &= R_l i_{d0} - \omega_{e0} L_q i_{q0} \\
    u_{q0} &= R_l i_{q0} + L_d \frac{d}{dt} i_{q0} + \omega_{e0} (L_d i_{d0} + \psi_t)
\end{align*}$$

where, $i_{d0}$ and $i_{q0}$ are the steady-state values of $d$-axis and $q$-axis current respectively, $\omega_{e0}$ is the steady-state value of electrical angular velocity.

The relationship among in the $d$-axis voltage steady-state value $u_{d0}$, $q$-axis voltage steady-state value $u_{q0}$, phase voltage steady-state value $u_{s0}$, phase angle $\gamma_0$ of the motor is shown in Eq.(7).

$$\begin{align*}
    u_{d0} &= u_{s0} \cos \gamma_0 \\
    u_{q0} &= u_{s0} \sin \gamma_0
\end{align*}$$

The steady-state value of electromagnetic torque $T_{e0}$ is shown in Eq.(8).

$$T_{e0} = \frac{3}{2} p_n l_d \psi_t$$

When the rotor position generates increment $\Delta \theta_c$, the phase angle increment of voltage vector in $dq$ coordinate system is $\Delta \gamma$, the steady-state values $u_{d0}$ and $u_{q0}$ can be expressed as Eq.(9).

$$\begin{align*}
    u_d &= u_{s0} \cos(\gamma_0 + \Delta \gamma) \approx u_{d0} - u_{q0} \Delta \gamma \\
    u_q &= u_{s0} \sin(\gamma_0 + \Delta \gamma) \approx u_{q0} + u_{d0} \Delta \gamma
\end{align*}$$

The increment of $d$-axis and $q$-axis voltage is shown in Eq.(10).

$$\begin{align*}
    \Delta u_d &= -u_{q0} \Delta \gamma \\
    \Delta u_q &= u_{d0} \Delta \gamma
\end{align*}$$
The relationship between phase angle increment $\Delta \gamma$ and rotor position increment $\Delta \theta_e$ is shown in Eq.(11).

$$\Delta \gamma = -\Delta \theta_e$$ (11)

When $L_d = L_q = L_s$, the dynamic equations of $d$-axis and $q$-axis voltage are shown in Eq.(12).

$$\begin{align*}
\Delta u_d & = \frac{R}{L_s} (\Delta i_d) + L_s \frac{d}{dt} (\Delta i_d) + L_s (\Delta \omega_e + \omega_0) (\Delta i_d) \\
\Delta u_q & = \frac{R}{L_s} (\Delta i_q) + L_s \frac{d}{dt} (\Delta i_q) + L_s (\Delta \omega_e + \omega_0) (\Delta i_q)
\end{align*}$$

(12)

where, $\Delta u_d$ and $\Delta u_q$ are the voltage increments of $d$-axis and $q$-axis respectively, and $\Delta\omega_e$ is the electrical angular velocity increment.

The voltage increment equations of $d$-axis and $q$-axis are shown in Eq.(12).

$$\begin{align*}
\Delta u_d & \approx R \Delta i_d + L_s \frac{d}{dt} \Delta i_d - L_s (\Delta \omega_e + \omega_0) \Delta i_d \\
\Delta u_q & \approx R \Delta i_q + L_s \frac{d}{dt} \Delta i_q + L_s (\Delta \omega_e + \omega_0) \Delta i_q
\end{align*}$$

(13)

where, $\Delta i_d$ and $\Delta i_q$ are the current increments of $d$-axis and $q$-axis respectively, $\Delta \omega_e$ is the angular velocity increment of rotor.

The electromagnetic torque increment $\Delta T_e$ is shown in Eq.(15).

$$\Delta T_e = \frac{3}{2} p_0 \Delta i_q \psi_f$$ (15)

The relationship between electromagnetic torque increment $\Delta T_e$ and rotor position increment $\Delta \theta_e$ is shown in Eq.(16).

$$G_{T\theta_e}(s) = \frac{\Delta T_e}{\Delta \theta_e} = \frac{3 p_0 (L_s^2 i_d + L_s \psi_f) s^2}{2 (R + L_s^2) + 2 (\omega_0 L_s) \psi_f}$$

(16)

The relationship between electromagnetic torque increment $\Delta T_e$ and rotor position increment $\Delta \theta_e$ is shown in Eq.(17).

$$G_{\omega e T_e}(s) = \frac{\Delta \omega_e}{\Delta T_e} = \frac{p_0}{J} \frac{1}{s}$$ (17)

**TABLE 1. Simulation parameters of magnetic bearing control system.**

| Name            | Parameter  |
|-----------------|------------|
| $i_0$           | 3.5A       |
| $x_0$           | 0.4mm      |
| $m$             | 30kg       |
| $k_{ms}$        | 27.49N/A   |
| $k_{max}$       | 210.46N/mm |
| $k_s$           | 6250V/m    |
| $\tau_s$        | 1.59×10^{-3}s |
| $k_p$           | 0.7A/V     |
| $\tau_p$        | 3.183×10^{-3}s |

**FIGURE 3. Simulation results of rotor’s air gap position.**

The relationship between rotor position increment $\Delta \theta_e$ and electrical angular velocity increment $\Delta \omega_e$ is shown in Eq.(18).

$$G_{\omega e \theta}(s) = \frac{\Delta \omega_e}{\Delta \theta_e} = \frac{1}{s}$$ (18)

The closed-loop transfer function of electric angular velocity increment $\Delta \omega_e$ to rotor position increment $\Delta \theta_e$ is shown in Eq.(19).

$$G_{\omega e \theta}(s) = -\frac{G_{T\theta_e}(s) G_{\omega e T_e}(s)}{1 + G_{T\theta_e}(s) G_{\omega e T_e}(s) G_{\theta e\omega}(s)}$$ (19)

**IV. SIMULATION VERIFICATION**

**A. SIMULATION VERIFICATION OF MAGNETIC BEARING CONTROL SYSTEM**

The simulation model of magnetic bearing control system is built in Matlab/Simulink. The simulation
The reference value of the rotor’s air gap position in the magnetic bearing control system is defined as 0.4mm. The simulation results of the rotor’s air gap position before and after the position control are shown in Fig.3. The rotor’s air gap position appears obvious divergence without position control, and the magnetic bearing control system can not be stable. The rotor’s air gap position can be stabilized at 0.4mm by using position control.

**B. SIMULATION VERIFICATION OF MOTOR OSCILLATION SUPPRESSION**

The relevant simulation parameters of ML-HSPMM are shown in TABLE 2. The simulation model of oscillation suppression control of ML-HSPMM is built.

The stability of ML-HSPMM corresponding to different moment of inertia is analyzed, and the effects before and after oscillation suppression control are compared.

The angular velocity increment with different moment of inertia is compared, of which the moment of inertia is $J = 0.0008 \, kg \cdot m^2$ and $J = 0.008 \, kg \cdot m^2$ respectively. Fig.4(a) shows the simulation result of angular velocity increment at $J = 0.0008 \, kg \cdot m^2$. The system has obvious divergence after 1.6s. Fig.4(b) shows the simulation result of angular velocity increment at $J = 0.008 \, kg \cdot m^2$. The system is unstable and oscillatory.

**TABLE 2. Simulation parameters of HSML-PMM.**

| Name          | Parameter value |
|---------------|-----------------|
| DC side voltage | 540V            |
| $L_d$         | 0.115mH         |
| $L_q$         | 0.115mH         |
| Rated speed   | 36000r/min      |
| Rated torque  | 40 Nm           |
| Rated voltage | 380V            |
| Rated current | 236A            |
| Pole pairs    | 1               |
| Switching frequency | 8kHz        |

**FIGURE 4. Simulation results of angular velocity increment with different moment of inertia.**

(a) Angular velocity increment when $J = 0.0008 \, kg \cdot m^2$

(b) Angular velocity increment when $J = 0.008 \, kg \cdot m^2$

**FIGURE 5. Simulation results of system root locus when $J = 0.008 \, kg \cdot m^2$.**

(a) When the speed is 10000r/min

(b) When the speed is 15000r/min

**FIGURE 6. Simulation speed results of ML-HSPMM used by oscillation suppression control.**

(a) The speed during oscillation

(b) The speed after oscillation suppression control

The stability of ML-HSPMM corresponding to different moment of inertia is analyzed, and the effects before and after oscillation suppression control are compared.

The angular velocity increment with different moment of inertia is compared, of which the moment of inertia is $J = 0.0008 \, kg \cdot m^2$ and $J = 0.008 \, kg \cdot m^2$ respectively. Fig.4(a) shows the simulation result of angular velocity increment at $J = 0.0008 \, kg \cdot m^2$. The system has obvious divergence after 1.6s. Fig.4(b) shows the simulation result of angular velocity increment at $J = 0.008 \, kg \cdot m^2$. The system is unstable and oscillatory.
The root locus of the system is analyzed according to the moment of inertia $J = 0.008\text{kg} \cdot \text{m}^2$. Fig.5(a) shows the root locus at 10000r/min and Fig.5(b) shows the root locus at 18000r/min. The results show that the system is unstable and oscillatory.

The speed tracking of ML-HSPMM before and after oscillation suppression control is shown in Fig.6. Fig.6(a) shows the speed simulation results during oscillation. The speed fluctuation is about 200r/min. Fig.6(b) shows the speed simulation results after oscillation suppression control. The value of speed fluctuation in Fig.6(b) is about 30r/min.

The acceleration and deceleration simulation result of ML-HSPMM is shown in Fig.7. During the period of 0~1s, the reference value of speed is 10000r/min. During the period of 1~2s, the speed reference value is 15000r/min. During the period of 2~3s, the reference value of speed is 10000r/min. During the period of 3~4s, the speed reference value is 0. ML-HSPMM can realize stable acceleration and deceleration operation by using the oscillation suppression control method.

V. EXPERIMENT VERIFICATION

The experimental platform of ML-HSPMM is shown in Fig.8, including HSPMM, magnetic bearing system controller, power converter, etc. The operation state of the ML-HSPMM at the high speed operation state is experimentally verified. The speed of the ML-HSPMM is 15000r/min, the output frequency of the motor is 250Hz, and the experimental results of AB line voltage and three-phase current are collected. Fig.9 shows the experimental results before and after the oscillation suppression control method is adopted. The voltage and current shown produce equal amplitude oscillation in Fig.9(a), and Fig.9(b) shows the experimental results when the ML-HSPMM oscillation suppression control method is adopted. The ML-HSPMM has superior performance.

VI. CONCLUSION

In this paper, only two aspects of magnetic levitation control system and HSPMM are discussed. Because of multi-source...
oscillation factors, the oscillation problem is inevitable when the speed is over 10000r/min. The oscillation suppression control method is proposed based on voltage feedforward control. The simulated and experimental results show that the proposed method can effectively improve the high-frequency reliable operation performance of magnetic bearing control system and solve the oscillation problem of ML-HSPMM.

This paper mainly introduces the oscillation suppression control method of HSPMM. At the same time, only the control method of magnetic levitation system is introduced. However, the influence of magnetic levitation system on motor oscillation and performance is not described, which can be studied in the future.

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