Control Design for Axial-Flux Permanent-Magnet Synchronous Motors in Flux-Weakening Region

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ABSTRACT : *An axial flux permanent magnet (AFPM) synchronous motor utilizing magnetic bearings instead of conventional ball bearings at both shaft ends can operate at rotational speeds significantly higher than its nominal speed. One approach to increasing the motor speed beyond its nameplate rating is to reduce the rotor pole magnetic flux (Ψ_p). This paper proposes a method to boost the speed of the AFPM motor above its nominal speed by introducing a negative d-axis current component (i_{sd}) to weaken the magnetic flux.*

Keywords: AFPM, *axial flux permanent magnet synchronous motor, optimal control above nominal speed*

INTRODUCTION

In terms of structure, the AFPM motor has its own particular specialists, in details, the stator module may include several types: A single module has one winding set and a dual module has two sets of winding sharing a common core and back-to-back establishment. Similarly, a single rotor module includes PMs only on one side, and in dual module one, both sides have PMs leaning against each other. In this paper, an object with two single module stators outside and one dual module rotor inside is designated as shown in Figure 1.

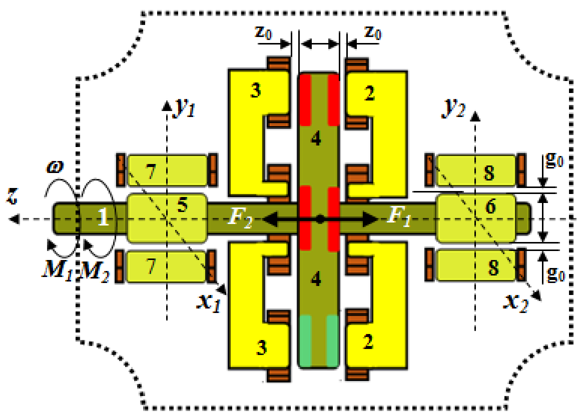

Figure 1: The AFPM motor section with integrated magnetic bearing at both ends of the motor sharp

When a three-phase voltage is applied to stator windings, different currents are generated, they will interact with the magnetics of rotor to generate torque (M) and the currents in phase windings (component id) of stator generate attractive force (F) based on the principle of the electromagnet. Thanks to special structure and above-mentioned operating principle, the rotor of the motor will not generate axial displacement although both ends of the shaft have magnetic bearings. It allows the absence of additional axial magnetic bearing; therefore, the motor structure is being compact. Due to the way of winding roll, the rotational magnetic field generates torques M_1 and M_2 on the same direction on the rotor shaft and generates the forces F_1 and F_2 between the rotor and the stators on opposite direction. The total torque ($M = M_1 + M_2$) is the sum of torques and axial forces ($F = F_1 - F_2$) which is the difference of two attractions. Based on structure and principle of operation, it can be considered as two AFPM motors that sharing a rotor or two motors with hard-wire shaft.

MATHEMATICAL MODEL OF THE AFPM MOTOR

The mathematical modelling of AFPM motor was developed in dq coordinate system, as presented on (1). The indicator 1 and 2 are present for the left-side motor and right-side motor, respectively.

$$\begin{cases} u_{sd1} = R_s i_{sd1} + L_{sd1}\dfrac{di_{sd1}}{dt} - \omega_s L_{sq1} i_{sq1} \\ u_{sq1} = R_s i_{sq1} + L_{sq1}\dfrac{di_{sq1}}{dt} + \omega_s L_{sd1} i_{sd1} + \omega_s \psi_p \\ u_{sd2} = R_s i_{sd2} + L_{sd2}\dfrac{di_{sd2}}{dt} - \omega_s L_{sq2} i_{sq2} \\ u_{sq2} = R_s i_{sq2} + L_{sq2}\dfrac{di_{sq2}}{dt} + \omega_s L_{sd2} i_{sd2} + \omega_s \psi_p \\ m_{M1} = \dfrac{3}{2} z_p \left[\psi_p i_{sq1} + i_{sd1} i_{sq1}(L_{sd1} - L_{sq1})\right] \\ m_{M2} = \dfrac{3}{2} z_p \left[\psi_p i_{sq2} + i_{sd2} i_{sq2}(L_{sd2} - L_{sq2})\right] \\ m_S = m_{M1} + m_{M2} = m_m + \dfrac{J}{z_p}\dfrac{d\omega}{dt} \\ F_S = k_1(i_{2d} - i_{1d}) + k_1(i_{2d} - i_{1d})z - k_2 z \end{cases} \quad (1)$$

Where: $k_1 = 2\dfrac{\mu_0^2 N^2}{g_0^2}\psi_p;\ k_2 = 2\dfrac{\mu_0}{S_p g_0}\psi_p^2.$

The voltage, current, and magnetic space vector of AFPM motor in two working areas are presented in Fig. 2 [1, 5, 7]. From (1), it is clearly seen that the torque of AFPM motor includes two parts: the major part with multiplication $\psi_p i_{sq}$ and the reactive part due to the difference of stator inductance (L_{sd} - L_{sq}) $\neq 0$). In all operating condition, the AFPM motor must produce a sub-torque to compensate the reactive part. The clear existence of the reactive part normally neglected in plans of conventional control. Ignoring that component helps to simplify control system and can be accepted in reality within nominal rotational speed, because in that range $i_{sd} = 0$ (Fig.2a). By contrast, above nominal speed range, to increase rotational speed, the magnetic flux must be decreased that requires a negative current component on the *d* axis. Therefore, the AFPM motor is operated in reduced magnetic flux and the amplitude of current will increase along with the rotational speed of the rotor (Fig.2b). Then, the proportion of reactive torque achieving significant amplitude cannot be ignored.

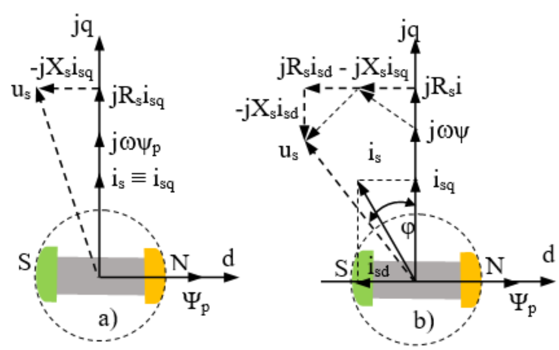

Figure 2*: State vector of voltage, current and the magnetic flux of AFPM motor in two working areas: a) Under nominal speed; b) Above nominal speed*

The limitation of current vector:

$$i_s = \sqrt{i_{sd}^2 + i_{sd}^2} < i_{sm} \quad (2)$$

The limitation of current (2) is a circular with radius ism in plane of (i_{sd}, i_{sq})

The limitation of voltage vector: From the formula of the voltage at steady state neglecting the resistance of stator:

$$u_{sd} = -\omega_s L_{sq} i_{sq};\ u_{sq} = \omega_s L_{sd} i_{sd} + \omega_s \psi_p$$

The fundamental maximum phase voltage of stator is determined by the immediate DC voltage:

$$|u_s| = \sqrt{u_{sd}^2 + u_{sd}^2} < u_{sm} \quad \textbf{(3)}$$

Where: u_{sm} is the maximum DC voltage of the inverter.

$$u_s^2 = u_{sd}^2 + u_{sd}^2 = (\omega_s L_{sq} i_{sq})^2 + (\omega_s L_{sd} i_{sd} + \omega_s \psi_p)^2 \qquad \textbf{(4)}$$

$$\frac{u_s^2}{\omega_s^2} = (L_{sq} i_{sq})^2 + (L_{sd} i_{sd} + \psi_p)^2 \qquad (5)$$

From (3) and (4), considering steady state and neglecting stator resistance, we obtain i_{sd}, i_{sq}. If φ is the angle difference between voltage vector of stator and q axis, replacing to (1), we have:

$$m_M = k_1 \left(\frac{u_s}{\omega_s}\right) cos\varphi - k_2 \left(\frac{u_s}{\omega_s}\right)^2 sin2\varphi \qquad (6)$$

$$k_1 = \frac{3z_p}{2}\psi_p \left(\frac{(L_{sd} - L_{sq})}{L_{sd}} - \frac{1}{L_{sq}}\right); \; k_2 = \frac{3z_p}{2}\left(\frac{L_{sd} - L_{sq}}{L_{sd} L_{sq}}\right)$$

CONTROL DESIGN FOR AFPM MOTOR

3.1. General control structure

The AFPM has a totally different structure to other typical electrical motors, so that, the control structure contains two separate control loops including the axial rotor position control and the rotational speed control loop for the motor. The general control structure for the AFPM motor is illustrated in Figure 3 [1, 3].

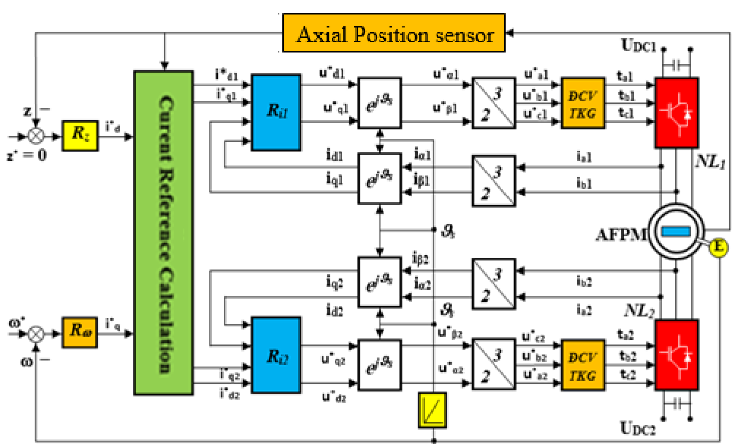

Figure 3: The vector control structure of the axial flux permanent magnet synchronous motor

3.2. Design of the controllers

3.2.1. Current control

The current control loop of AFPM motor is extracted from Fig. 2 and the following formulas:

$$i_{sd} = (u_{sd} + i_{sq}.w_s.L_{sq})W_{sd}$$
$$i_{sq} = (u_{sq} - i_{sd}.w_s.L_{sd})W_{sq} \qquad (7)$$

$$i_{sd} = \frac{1}{1 + W_{sd}.W_{sq}.w_s^2.L_{sd}.L_{sq}}(W_{sd}u_{sd} + w_s.L_{sq}.W_{sd}.W_{sq}.u_{sq})$$
$$i_{sq} = \frac{1}{1 + W_{sd}.W_{sq}.w_s^2.L_{sd}.L_{sq}}(-w_s.L_{sd}.W_{sd}.W_{sq}.u_{sd} + W_{sq}u_{sq}) \qquad (8)$$

$$W(s) = \frac{W_i.W_{nl}}{1 + W_{sd}.W_{sq}.w_s^2.L_{sd}.L_{sq}} \begin{bmatrix} W_{sd} & w_s.L_{sq}.W_{sd}.W_{sq} \\ w_s.L_{sd}.W_{sd}.W_{sq} & W_{sq} \end{bmatrix} \qquad (9)$$

Where: $W_{sd} = \frac{1/R_s}{T_{sd}s+1}$; $W_{sq} = \frac{1/R_s}{T_{sq}s+1}$; $W_{nl} = \frac{K_{nl}}{T_{nl}s+1}$; $W_i = \frac{K_i}{T_i s+1}$

To archive the desired quality as the closed-loop transfer function of module optimal standard is:

$$W_m(s) = \frac{1}{1 + 2T_s s + 2_{sd}.T_s^2 s^2} \qquad (10)$$

The first task is conducting the decoupling of the current components.

The current decoupling regulator is determined as follows: $W_R(s) = W_m(s)(I - W_m(s))^{-1}.W(s)$ (11)

When choosing $T_s = T_{si} = 2T_i = 0{,}002$, we have $T_s^2 << 1$ that can be ignored. Therefore, it is possible to define the transfer function of channel separation regulators for current control loop:

$$W_R(s) = \frac{1}{4T_i.K_{nl}K_i}\begin{bmatrix} L_{sd}(1 + \frac{1}{T_{sd}s}) & \frac{-w_s.L_{sq}}{s} \\ \frac{w_s L_{sd}}{s} & L_{sq}(1 + \frac{1}{T_{sq}s}) \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \qquad \left.\begin{aligned} R_{11}(s) &= \frac{1}{4T_i.K_{nl}K_i}L_{sd}(1 + \frac{1}{T_{sd}s}) \\ R_{12}(s) &= \frac{1}{4T_i.K_{nl}K_i}\frac{w_s L_{sd}}{s} \\ R_{21}(s) &= \frac{1}{4T_i.K_{nl}K_i}\frac{-w_s L_{sd}}{s} \\ R_{22}(s) &= \frac{1}{4T_i.K_{nl}K_i}L_{sq}(1 + \frac{1}{T_{sq}s}) \end{aligned}\right\} \quad (12)$$

3.2.2. Axial motion control

For simplicity, assuming that the radial movement of the rotor is controlled by two ideal radial bearings. Therefore, the axial motion is independent of the radial movement and can be expressed as follows [1,2,3,4]:

$$F - F_L = m\ddot{z} \qquad (13)$$

Where m is the weight of movement parts and F is an axial force.Then insert (1) to (14), we obtain:

$$m\ddot{z} + F_L = k_1(i_{2d} - i_{1d}) + k_1(i_{2d} - i_{1d})z - k_2 z \qquad (14)$$

where $k_1 = 2\frac{\mu_0^2 N^2}{g_0^2}\psi_p;\ k_2 = 2\frac{\mu_0}{S_p g_0}\psi_p^2.$

It is clearly seen that this system is unstable. To stabilize, a controller with the derivative component is applied. The axial-gap control loop includes the transfer function of the current control loop and axis motion function. Because of the uncertainty of axial load, therefore, it must be processed in the first step as an external disturbance.To eliminate static error, the PID controller is used. The transfer function of PID controller is expressed as follow:

$$G_{cz}(s) = K_P + \frac{K_I}{s} + K_D s \qquad (15)$$

The system will be stable when the parameters of the controller satisfying:

$$\begin{cases} K_P > \dfrac{K_2}{K_1 K_z}; K_I > 0; K_D > 0 \\ K_I < \dfrac{K_D(K_1 K_P + K_2)}{m} \end{cases} \qquad (16)$$

3.2.3. Speed control

For all types of motors, the discrepancy between the electromagnetic torque M and the load torque M_L generates rotor's acceleration following mechanical characteristic of the motor transmissions. The rotational motion equation can be written as [1,3,4,5]:

$$M - M_L = J\frac{d\omega}{dt} \text{ or } \frac{\omega}{M - M_L} = \frac{1}{Js} \qquad (17)$$

The torque can be controlled by the axial current q as presented in equation (1); therefore, the speed control loop is expressed as in Figure 4.

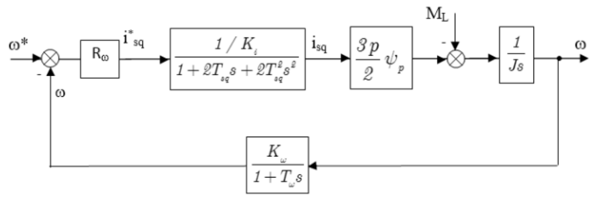

***Figure 4**: The speed control loop*

The closed-loop transfer function can be expressed as follow:

$$W_K(s) = \frac{R_\omega W_0}{1 + R_\omega W_0} = \frac{KR_\omega}{s(T_s^{'}s + 1) + KR_\omega} \qquad (18)$$

The speed control loop is the inertial integration; therefore, we apply a symmetric optimization standard with criterion function:

$$W_C(s) = \frac{1 + 4T_s s}{1 + 4T_s s + 8T_s^2 s^2 + 8T_s^3 s^3} \qquad (19)$$

Equalizing (18) and (19): $\frac{KR_\omega}{s(T_s^{'}s + 1) + KR_\omega} = \frac{1 + 4T_s s}{1 + 4T_s s + 8T_s^2 s^2 + 8T_s^3 s^3}$

Choosing: 2T’s = T_s, we can obtain the following result by solving the abovementioned equation:

$$R_\omega = \frac{1 + 4T_s s}{K 8T_s^2 s} = \frac{1}{8KT_s^2 s} + \frac{1}{2KT_s} \qquad (20)$$

SIMULATION RESULTS

4.1. Parameters of the motor

R_s = 2,3 Ω; L_{sq} = 9,6.10^{-6} H; L_{sd} = 8,2.10^{-6}H; Tsq = 4,2.10^{-6}; T_{sd} = 3,56.10^{-6}; Ψ_p = 0,0126Wb;Zp = 1;g_0 = 1,7.10^{-3} m; m_{rotor}=0,235kg;Jr = 0,0000082 kgm^2; μ_0 = 4π x 10^{-7}H/m;Knl = 5; K_i = 1; T_i = 0,001; K_ω = 0,00417; T_ω = 0,1; $T_{s\omega}$ =T_ω+2T_i; 2T’$_s$ = $T_{s\omega}$.

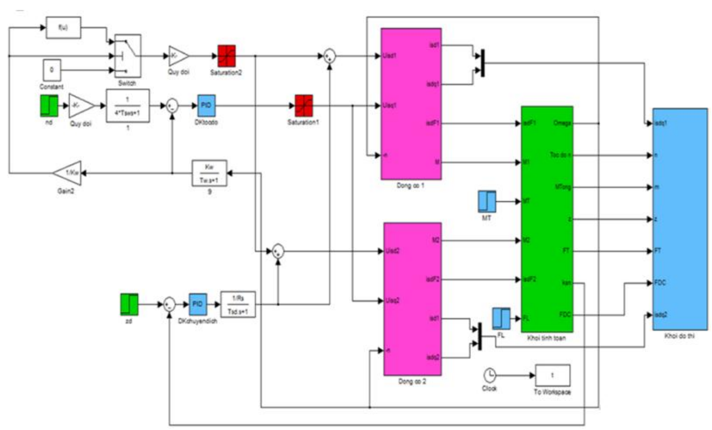

***Figure 5**: The simulation model of the AFPM motor*

4.1. Simulation results

a. With the nominal speed n = 3000 rpm; m_T = 0.08Nm, F_T = 0.

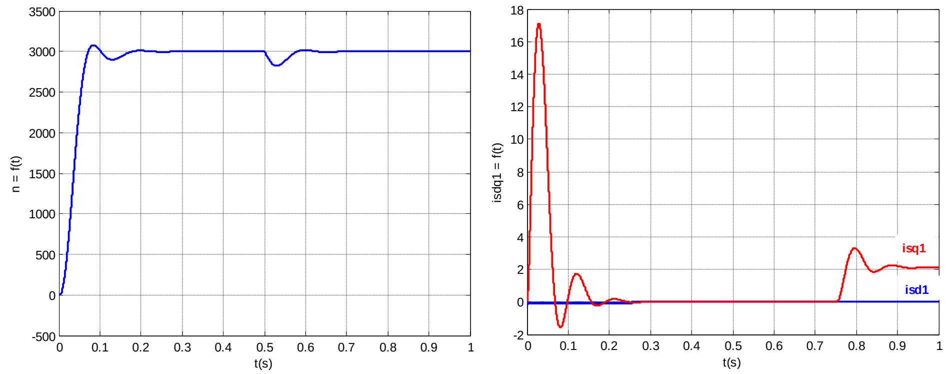

Figure 6*: Simulation result with n=3000rpm*

b. With the speed above the nominal speed n=4000rpm; m_T = 0,08Nm; $F_T \neq 0$.

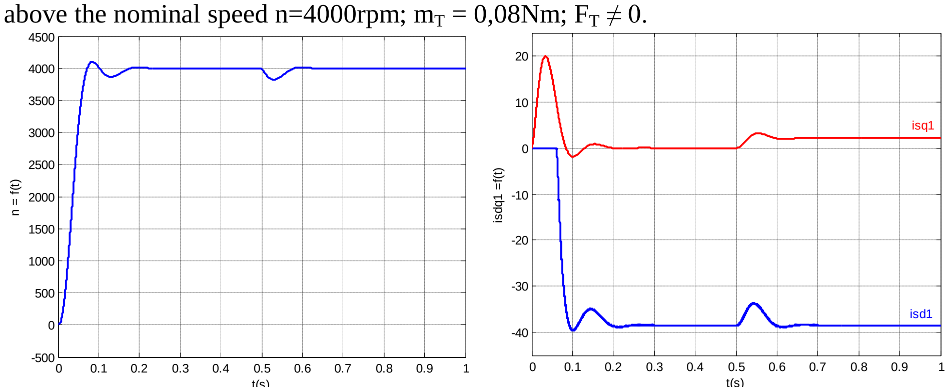

Figure 7*: Simulation result with above nominal speed n = 4000 rpm*

CONCLUSION

Using the AFPM motor that has special structure with magnetic bearings at both two ends of its shaft (Fig. 1) generated two control loops: the speed control loop and the axial motion of rotor (in this case, we consider that the bearings carry out theirs assigned tasks). By applying the rotorflux-orientedcontrol method (T^4R), the followings are achieved:

- Adjusting the motor speed above the nominal speed by reducing magnetic flux thanks to control the d axis current componentthat is opposite to the pole magnetic $\psi_p$in order to maintain the motor torque.

- Consequently, keeping the rotor in the center of the motor as a result of the axial displacement control loop.

- Further researches can be considered are: improving the quality control for motor and ensuring the optimal torque when the magnetic flux reduced;Experimental study on the control of the AFPM motor.

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