Designing adaptive current controller for two axial flux permanent magnet synchronous motors connected by one shaft

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Abstract *— When choosing axial flux permanent magnet (AFPM) motor with the configuration of double stator module at two sides of in-between disc-shaped rotor, it can be obviously considered as two mechanical coupled motors. With the use of magnetic bearings at the two ends of the shaft, the rotor can be rotating and also have these motions: vertical translation, horizontal translation and gyroscopic effects. At that time, the difference between electric currents in the two stators will be significant. This paper introduces a design of adaptive current controller to balance out the loads onto the mentioned motors.*

Keywords — *Keywords: AFPM, MRAC, PID.*

Symbol

Symbol	Unit	Meaning
A,B, N,		Matrix of model
S	N	Electromagnetic force
F		Positive definite matrix
P, Q		Lyapunov function
V	Nm	Electromagnetic torque
M		

Abbreviation

AFPM	Axial Flux Permanent-Magnet
MRAS	Model REFERENCE Adaptive System
PID	Proportional - Integral - Derivative
PMSM	Permanent Magnet Synchronous Motor

I. INTRODUCTION

Recently, Permanent Magnetic Synchronous Motors (PMSM) are widely used in high quality speed-control electrical drive systems because of many outstanding features in comparison with those of the other motor types [1,2].

A fundamental difference of Axial Flux Permanent Magnet Synchronous Motor (AFPM) in comparison with other types is that the motor's back-electromotive force has a trapezoidal shape due to the concentrated windings (others take sinusoidal shape because of the distributed windings). The trapezoidal shape of back-electromotive force causes the AFPM to have mechanical property like that of DC motors with high power density, high electromagnetic torque generation, and high efficiency.

Fig. 1 shows a cross view of an AFPM with radial bearings on both sides of its shaft [3, 4, 5, 6, 7, 8]. The motor has two stators at both sides and disc-shape permanent magnet double rotor. This special structure enables the motor to have the ability to generate both rotating torque on its shaft and axial attractive forces to keep the rotor at nominal position.

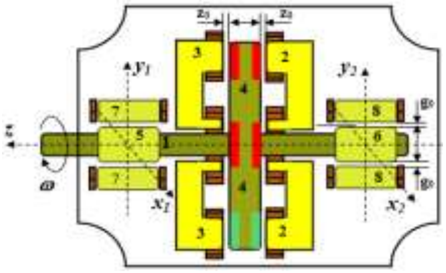


Fig. 1 *The sectional view of a AFPM with built-in bearings from two sides of the shaft (1: Shaft; 2,3: Stator and windings of the right, the left motor; 4: Permanent magnet rotor of the motor;5,6: Rotor of the left and the right magnetic bearings; 7,8: Stator and windings of the left, the right magnetic bearings; z_0, g_0: Nominal air gap between rotor and stator of the motor and the magnetic bearings)*

A conspicuous characteristic of the AFPM is that its diameter is several times bigger than its axial dimension (for radial flux motor, its diameter is usually much smaller than the length of the motor). Because the axial magnetic bearing is not added like conventional motors with integrated magnetic bearings, the size of the motor and the drive system will be significantly reduced. For the sake of simplicity of controlling, the two stators of the motors are supplied by independent inverters. Obviously, we can consider these as the two separate AFPMs coupled to one shaft.

The figure Fig. 2 introduces the stator structure with concentrated windings of phases A, B, C and disc-shape double rotor with permanent magnets polarized N, S on its surface.

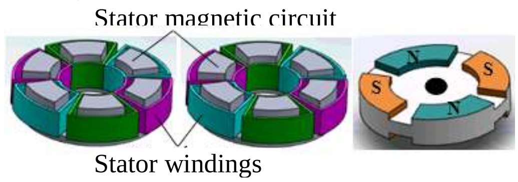


Fig. 2 *3D Illustration of the structure of stator and rotor of AFPM*

During a working process, the motor can be affected by a noise (mostly the load torque) causing the rotor shaft to be translated along the radial axes x, y or moved along the z axis with respect to the stator center axis (in normal state, the center axis is coincided with the z axis). That could even lead to the rotor shaft to be leaned some angles with respect to the stator center axis to the x, y axis directions and its trajectory, in general forms two cones that share the same peak at the center axis so-called the gyroscopic effects. When this happens, the difference between the electric currents in the two stators will be significant.

This paper presents an adaptive current controller designed based on Lyapunov theory for load balancing of the AFPM. The multi-variable mathematical model and the coordinate transformations are used in order to have an equivalent model of a direct current (DC) motor will be presented in section II. The design of Lyapunov-based MRAS and a performance evaluation of the system through simulation will be presented in section III of the paper.

II. MATHEMATICAL MODEL OF THE AFPM SYNCHRONOUS MOTORS

A. *Multi-variable mathematical model of AFPM motors*

As analyzed above, an AFPM is basically the two axial flux permanent magnet synchronous motors that are coupled on one shaft. Thus, the mathematical model of the synchronous motor with stator on the right of the rotor is called the motor number 1. According to the directed magnetic field in the two-phase synchronous rotating coordinate dq [6,7,8, 9] we have:

$$\begin{cases} \begin{vmatrix} u_{d1} \\ u_{q1} \\ U_p \end{vmatrix} = \begin{vmatrix} R_1 + L_s p & -wL_q & L_{mp} \\ wL_d & R_1 + L_s p & wL_p \\ L_{mp} & 0 & R_p + L_p p \end{vmatrix} \cdot \begin{vmatrix} i_{d1} \\ i_{q1} \\ I_p \end{vmatrix} \\ M_{dt1} = n_p \dfrac{L_m}{L_p} y_p i_{q1} \end{cases} \quad (1)$$

This simple relationship is completely similar to the torque equation of a DC motor.

Similarly, the mathematical model of the synchronous motor number 2 with stator on the left of the rotor is:

$$\begin{cases} \begin{vmatrix} u_{d2} \\ u_{q2} \\ U_p \end{vmatrix} = \begin{vmatrix} R_1 + L_s p & -wL_q & L_{mp} \\ wL_d & R_1 + L_s p & wL_p \\ L_{mp} & 0 & R_p + L_p p \end{vmatrix} \cdot \begin{vmatrix} i_{d2} \\ i_{q2} \\ I_p \end{vmatrix} \\ M_{dt2} = n_p \dfrac{L_m}{L_p} y_p i_{q2} \end{cases} \quad (2)$$

The state-space equations of the AFPM can be presented in full form as:

$$\dot{\underline{x}} = A\underline{x} + B\underline{u} + N\underline{x}w_s + S y_p w_s \quad (3)$$

$$\underline{x} = \begin{vmatrix} i_{sd1} \\ i_{sq1} \\ i_{sd2} \\ i_{sq2} \end{vmatrix}; \; A = \begin{vmatrix} 1/T_{sd1} & 0 & 0 & 0 \\ 0 & 1/T_{sq1} & 0 & 0 \\ 0 & 0 & 1/T_{sd2} & 0 \\ 0 & 0 & 0 & 1/T_{sq2} \end{vmatrix};$$

$$S = \begin{vmatrix} 0 \\ \dfrac{1}{L_{sq1}} \\ 0 \\ \dfrac{1}{L_{sq2}} \end{vmatrix}; \; B = \begin{vmatrix} 1/L_{sd1} & 0 & 0 & 0 \\ 0 & 1/L_{sq1} & 0 & 0 \\ 0 & 0 & 1/L_{sd2} & 0 \\ 0 & 0 & 0 & 1/L_{sq2} \end{vmatrix};$$

$$N = \begin{vmatrix} 0 & 0 & 0 & L_{sq1}/L_{sd1} \\ 0 & 0 & L_{sd1}/L_{sq1} & 0 \\ 0 & L_{sq2}/L_{sd2} & 0 & 0 \\ -L_{sd2}/L_{sq2} & 0 & 0 & 0 \end{vmatrix}$$

B. *Determining the sum of the attractive forces along the rotor shaft [3, 4, 5]*

The attractive forces of the motor are the interaction of per-pole magnetic flux y_p of the rotor with the direct component of the stator current. When rotor moves axially, the air gap between the rotor and the stator changes, it will be increased to $>z_0$ on one side and the other side will be $< Z_0$. At that time, the force F appears to attract the rotor to its nominal position with the uniform gap between the stators.

$$z_0: \; F = F^+ - F^-$$

$$F = 2\frac{m_0}{S_p} y_p \left[y_p \frac{z}{g_0} + (y_{1w} - y_{2w}) \right] \quad (4)$$

In which, the polarized magnetic flux y_p is known; S is the sectional area, iron-core, air gap or magnetic paths, N is the number of turns, i is instantaneous current, z_0 is the air gap at normal position, z is a displacement of the rotor.

In the equivalent model of the motor, we have:

$$F = F^+ - F^- = \frac{N^2 m_0 wl}{g_0^2} I_0 i_s + 2\frac{N^2 m_0 wl}{g_0^3} I_0 i_s z \quad (5)$$

The mathematical model of AFPM is presented on Fig. 3.

To make it simpler in designing the controller, the nonlinear matrices, noise vectors and noise components with fixed amplitudes are ignored. Matrices A and B of the AFPM have the following component values:

$T_{sq} = 4{,}2.10^{-6}$ [s]; $T_{sd} = 3{,}56.10^{-6}$ [s]; $L_{sq} = 9{,}6.10^{-6}$ H; $L_{sd} = 8{,}2.10^{-6}$ H.

The adaptive control structure of the current loop of the motor number 2 (with stator is in the left of the rotor) as shown in Fig. 5.

III. DESIGNING MRAS BASED ON LYAPUNOV THEORY

A. *Introduction*

The Model Reference Adaptive Systems (MRAS) is mostly employed for the direct adaptive control. The philosophy behind the application of MRAS is that the expected characteristics of the system are given by reference model.

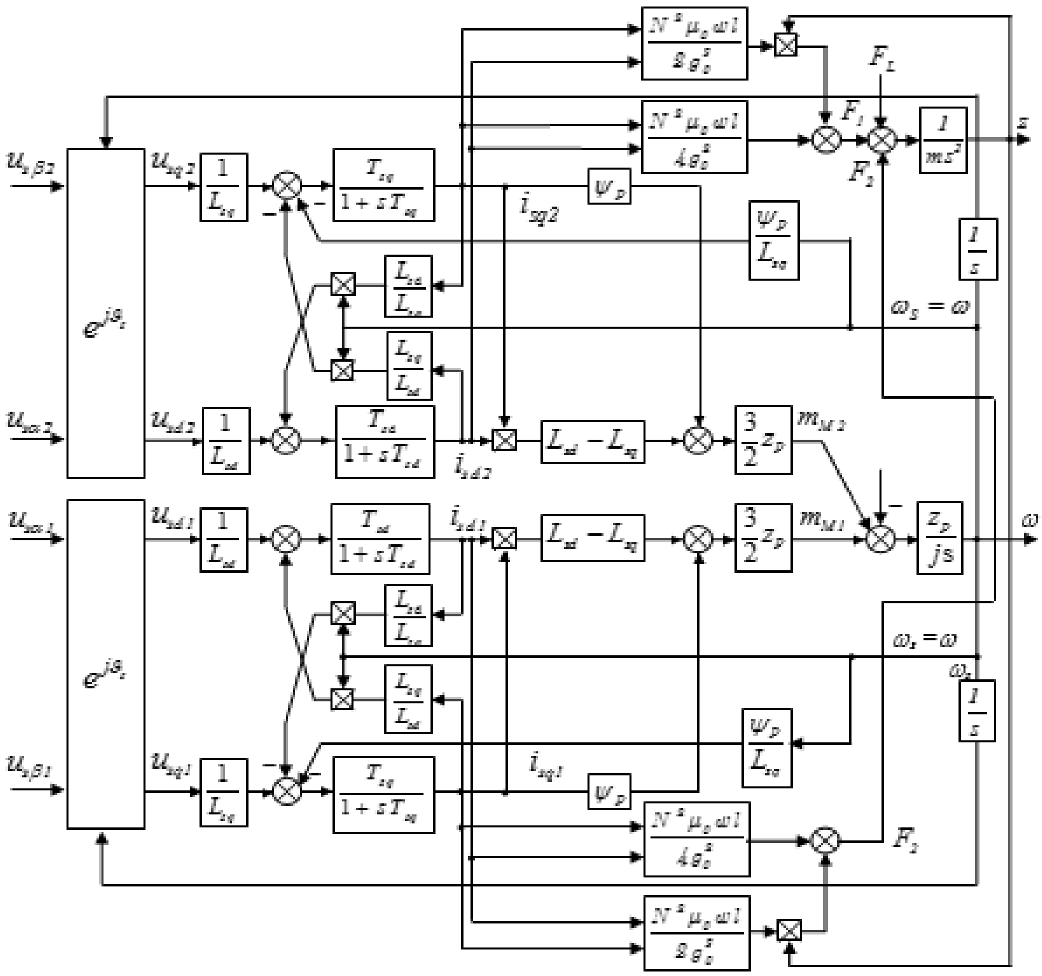


Fig. 3 *The full mathematical model of the permanent magnet synchronous axial flux motor with integrated axial magnet bearing (1), (2) và (5)*

When the output response of the process differs from the "ideal" response defined by the reference model, the plant will be changed in two ways: by tuning controller's parameters or by adding supplementary inputs to the process. The performance of the system is assessed through the quadratic differential integration standard of the error *e(t)* [9, 10]:

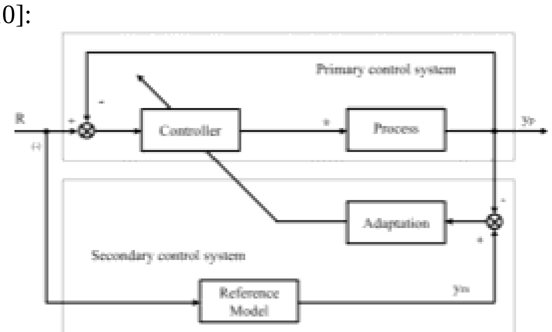


Fig. 4 *Direct MRAS – Parameter adaptive system [11]*

$$C = \int_0^T e^2(t)dt \qquad (6)$$

In which: $e = Y_m - Y_p$ (7)

Y_m, Y_p are outputs of the reference model and the real model.

Aside from minimizing the error between the output signal of the subject and the reference model, all the state variables of the subject are taken into account. When state variables of the process are denoted as (X_p) and state variables of the reference model are denoted as (X_m), the error vector is defined as: $e = X_m - X_p$ (8)

In this case, determining the performance of the system according to (7) can be transformed to minimize the integral follows:

$$C = \int_0^T e^T P e\,dt \tag{9}$$

Where, P is a positive definite matrix.

B. Adaptive PD controller

The structure depicted in Fig. 6 can be used as an adaptive PD controlled system. A second-order process with transfer function $\frac{K}{s(s+a)}$ is controlled with the aid of a PD-controller. The parameters of this controller are K_p and K_d. Variations in the process parameters K and a can be compensated for by variations in K_p and K_d. The desired performance of the complete feedback system is described by the transfer function:

$$\frac{x_{1m}}{u} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n}$$ with $\omega_n = 1$ and $\zeta = 0.7$.

$$C = \int_0^T e^2(t)\,dt \tag{6}$$

$$e = Y_m - Y_p \tag{7}$$

Describe the process in state space:

$$\begin{pmatrix} \dot{x}_{1p} \\ \dot{x}_{2p} \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ KK_p & -(a+K_d) \end{pmatrix} \begin{pmatrix} x_{1p} \\ x_{2p} \end{pmatrix} + \begin{pmatrix} 0 \\ KK_p \end{pmatrix} u \tag{10}$$

For the design of this adaptive system it is easier to describe the system with the aid of the state variables ε and x_2

$$e_p = u - x_{1p};\ \dot{e}_p = -\dot{x}_{1p} = -x_{2p} \tag{11}$$

The process model can be written as:

$$\dot{x}_p = A_p x_p + B_p u \tag{12}$$

$$x_p = \begin{pmatrix} e_p \\ x_{2p} \end{pmatrix} A_p = \begin{pmatrix} 0 & -1 \\ KK_p & -(a+K_d) \end{pmatrix} B_p = \begin{bmatrix} 0 \\ KK_p \end{bmatrix} \tag{13}$$

The same way for the reference model we have:

$$s_m = u - x_{1m};\ \dot{s}_m = -\dot{x}_{1m} = -x_{2m} \tag{14}$$

The description of the reference model is:

$$\dot{x}_m = A_m x_m + B_m u \tag{15}$$

$$x_m = \begin{pmatrix} s_m \\ x_{2m} \end{pmatrix} A_m = \begin{bmatrix} 0 & -1 \\ \omega_n^2 & -2\zeta\omega_n \end{bmatrix} B_m = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{16}$$

Subtracting Equation (13) from Equation (16) yields

$$e = x_m - x_p;\ A = A_m - A_p;\ B = B_m - B_p \tag{17}$$

The necessary steps to design the adaptive control system based on Lyapunov method are as follows:

1. Determine the differential equation for *e:*

$$e = x_m - x_p \tag{18}$$

where x_m and x_p are states of the reference model and the process, respectively.

2. Choose a Liapunov function *V*:

$$V(e) = e^T P e + a^T \alpha a + b^T \beta b \tag{19}$$

where P is an ‘arbitrary’ definite positive symmetrical matrix; a and b are vectors which contain the non-zero elements of the A and B matrices; α and β are diagonal matrices with positive elements which determine the speed of adaptation.

With this choice of P, α and β, V(e) is a definite positive function. Differentiation of V(e) yields:

$$\dot{V}(e) = \dot{e}^T P e + e^T P \dot{e} + 2a^T \alpha \dot{a} + 2b^T \beta \dot{b} \tag{20}$$

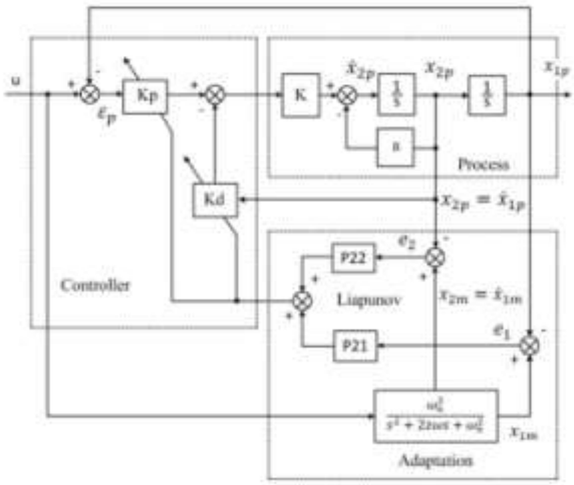
3. Determine the condition under which $\dot{V}(e)$ is negative definite.

4. Solve P from $A_m^T P + A_m P = -Q$ (21)

where Am is the reference model matrix and Q is a positive definite symmetrical matrix. These yields, after some mathematical manipulations, the complete adaptive laws in integral form [11]:

$$\begin{aligned} K_p &= \alpha_p \int [(p_{21}e_1 + p_{22}e_2)e_p]\,dt + K_p(0) \\ K_d &= \alpha_d \int [(p_{21}e_1 + p_{22}e_2)x_{2p}]\,dt + K_d(0) \end{aligned} \tag{22}$$

where α_p and α_d are called the adaptive gains, and e_1, e_2, s_p, and x_{2p} are defined in Fig. 7; g_{21} and g_{22} are elements of the P matrix. The resulting adaptive system has been given (see Fig. 5).



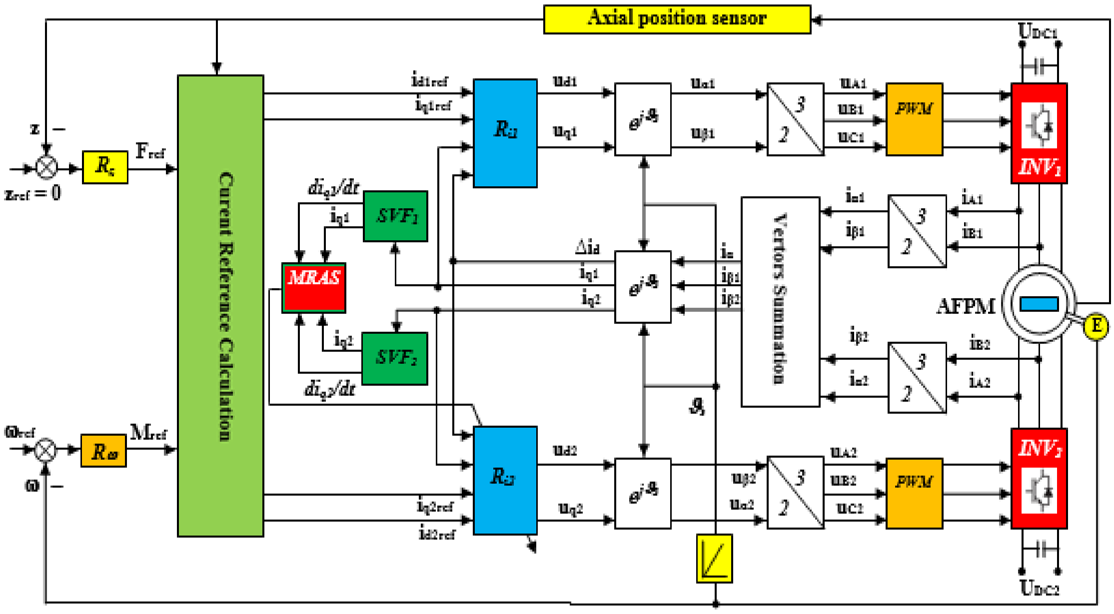


Fig. 5 *Adaptive control structure for current loop of the second motor (which has stator on the left of the rotor)*

C. *Adaptive current controller for the second motor*

The procedure is used to design an adaptive PD controller with the method of Liapunov was shown in Section B. Based on Equation (22) the adjustable parameters of the controller are given by:

$$K_p = \alpha_p \int [(P_{21}e_1 + P_{22}e_2)e]dt + K_p(0)$$
$$K_d = \alpha_d \int [(P_{21}e_1 + P_{22}e_2)b\dot{I}_2]dt + K_d(0) \quad (23)$$

where α_p and α_d are the speed of adaptation; ($e_1 = I_1 - bI_2$, $e_2 = \dot{I}_1 - b\dot{I}_2$; $I_1 = i_{q1}$; $I_2 = i_{q2}$) P21 and P22 are elements of the P matrix, obtained from the solution of the Liapunov equation: $A_m^T P + A_m P = -Q$

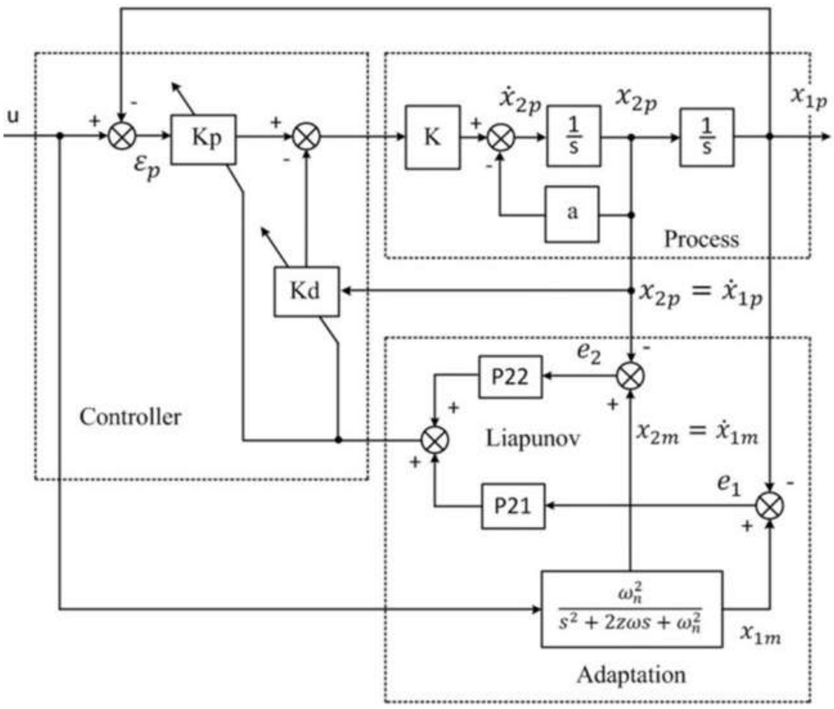


Fig. 6 *Control configuration of the adaptive PD controlled system [11]*

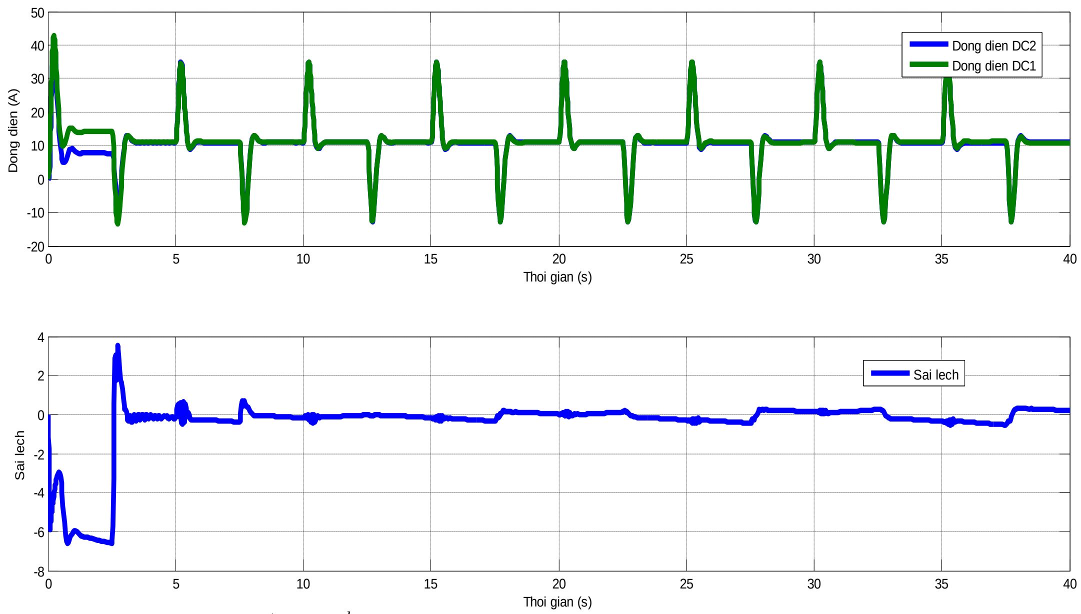


Fig. 7 *The currents of the 1st and 2nd motor (upper figure), current errors of the two motors (lower figure)*

In this equation Q must be a positive definite matrix; A_m belongs to the desired reference model (with $\omega_n = 1$ and $2z\omega_n = 1.4$). The following numerical values are used:

$$A_m = \begin{pmatrix} 0 & 1 \\ -1 & -1.4 \end{pmatrix} \quad Q = \begin{bmatrix} 10 & 15 \\ 15 & 10 \end{bmatrix} \tag{24}$$

These settings lead to the following Liapunov gains:

$$p_{21} = 0.05; \; p_{22} = 0.36 \tag{25}$$

The adaptive gains determine the speed of adaptation and they can ‘arbitrarily’ be chosen. The following settings are $\alpha_p = 0.1$, and $\alpha_d = 0.2$

The simulation results are shown in Fig. 7. After only one step the currents from both motors are adjusted to be balance. The difference between the two currents is approximately zero.

IV. CONCLUSION

The simulation results of using MRAS for balancing the currents of the two permanent magnet synchronous axial flux motors coupled by one shaft show that the current of the second motor rapidly follows up the current of the first motor. This enables the loads of the two motors to balance out. The more important thing is that the rotor of the motor is kept at a nominal position far away from the stator with a distance of z_0.

Further studies will be conducted experimentally to prove the results gained through theories and simulation mentioned above.

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