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Online Parameter Estimation of an Interior Permanent Magnet Synchronous Motor using Model Reference Adaptive System Method

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Abstract
Due to many advantages such as high efficiency, low weight, high dynamic response, etc., Permanent Magnet Synchronous Motors (PMSMs) are attracting more attention in many practical applications, including industrial drives, pumps, fans and electric vehicles.
A common practice is using a vector controlled PMSM with decoupling controllers to control the torque and flux independently. The parameters of the machine may change during operation due to heat and saturation effects; also, all the parameters of the machine may not be known. Therefore, the drive system should be able to estimate the parameters of the motor real-time; otherwise, there will be detuning effects in the performance of the overall system.
This paper aims at estimating the electrical parameters of a PMSM using Model Reference Adaptive System (MRAS) observers. The adaptation mechanism is designed using Lyapunov's stability criterion in order to guarantee stability of the estimator.
Simulation results of a PMSM under vector control with the proposed parameter estimators verify the efficiency and accuracy of the method.

Keywords: parameter estimation, Model Reference Adaptive System, vector control, Permanent Magnet Synchronous Motor, Lyapunov's stability criterion

Introduction

Parameter estimation of electrical motors is important in control of electrical drives. If there is a good and stable parameter estimator in the system, control performance will be suitable even under change of temperature or saturation conditions.
Estimation methods are classified in a broad sense into two groups, namely: offline and online methods. Offline methods are simple and easy to implement but have the disadvantage that the estimated parameters may not be the ones in the actual operating point of the motor; on the other hand, online (or real-time methods) take care of parameter changes due to change of the operating point and are of course usually more complex to implement.
This paper uses the Model Reference Adaptive System (MRAS) method with Lyapunov's stability theorem to estimate the electrical parameters of the Permanent Magnet Synchronous Motor (PMSM). This method has the advantage to be simpler to implement in comparison with methods using artificial intelligence algorithms [1,2]. The PMSM under study is of the Interior Permanent Magnet Synchronous Motor (IPMSM) type, where the d-axis and q-axis inductances are not equal, making design of estimators more difficult in comparison with the surface mounted PMSMs, studied in [3,4]. Another distinction of the current paper is that the stability of estimation is guaranteed, in contrast to the research work presented in [5]; also, laws are derived to estimate all the four electrical parameters, in comparison with [6] where only the stator resistance and permanent magnet flux linkage have been estimated.
Hybrid methods have been used in [7-9] where the output of the adaptive model is optimized using such algorithms as whale optimization and Kalman or extended Kalman filtering are also incorporated. Reference [10] uses the Recursive Least Squares (RLS) method with vector control to estimate the parameters. Estimation of parameters is also used in systems with Direct Torque Control (DTC) [11].

Dynamic equations of the PMSM

The voltage equations governing the dynamic behavior of the motor, expressed in the rotor reference frame, are as follows:

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q$$
$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \psi_f \quad (1)$$

Where the "d" and "q" subscripts point out the d-axis and q-axis variables and parameters, respectively; ω_r is the rotor speed and ψ_f is the permanent magnet flux linkage. Based on the dynamic equations, the equivalent d-q circuits in the rotor reference frame can be drawn, as shown in Figure 1.

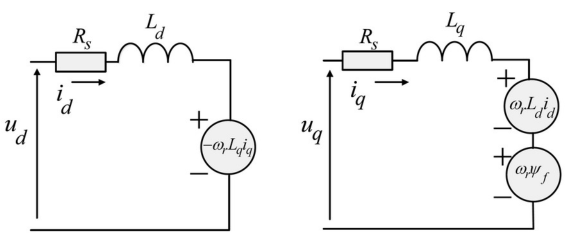

Figure 1. Equivalent d-q circuits of a PMSM

These equations can be rewritten in the standard state space equations form, as:

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \omega_r \frac{L_q}{L_d} i_q + \frac{1}{L_d} u_d$$
$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \omega_r \frac{L_d}{L_q} i_d - \omega_r \frac{\psi_f}{L_q} + \frac{1}{L_q} u_q \quad (2)$$

The above equations will be used to design the estimation laws.

Motor control strategy

The adopted control method is the well-established vector control with permanent magnet flux orientation. The block diagram of the control system is shown in Figure 2. The d-axis reference current (i_d^*) may be taken to be zero, or may be negative to make use of the reluctance torque. As evidenced in [12], only two parameters can be simultaneously estimated using two electrical equations of (2). If the aim is to estimate more than two parameters, one solution is two change the d-axis reference current to change the operating point.

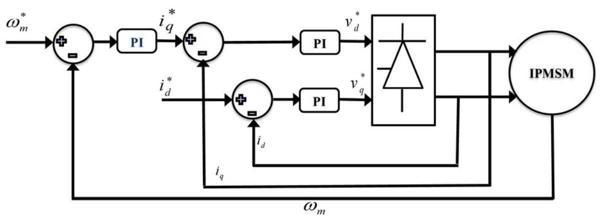

Figure 2. Block diagram of vector-controlled motor

Model Reference Adaptive System parameter estimation

One common estimation method is the Model Reference Adaptive System (MRAS) observer. In this strategy, there is a reference model, which does not include the unknown parameters, and an adaptive model, which includes the unknown parameters to be estimated. An adaptation mechanism changes the estimated parameters until the error signal, which is the difference of the outputs of the two models, approaches zero. The schematic of the parameter estimation method used in this paper is as shown in Figure 3.

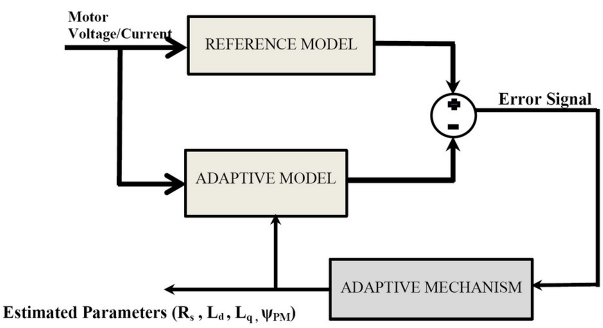

Figure 3. Schematic of the MRAS parameter estimation method

Defining the following vectors:

$$x = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, u = \begin{bmatrix} u_d \\ u_q \end{bmatrix} \quad (3)$$

The state space equations take the form:

$$x^{\bullet} = A.x + B.u + C \quad (4)$$

Where:

$$A = \begin{bmatrix} -\frac{R_s}{L_d} & \frac{L_q}{L_d}\omega_r \\ -\frac{L_d}{L_q}\omega_r & -\frac{R_s}{L_q} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}, C = \begin{bmatrix} 0 \\ -\omega_r \frac{\psi_f}{L_q} \end{bmatrix} \quad (5)$$

Estimation of the stator resistance

Assuming that the only unknown parameter is the stator resistance, and taking the estimated currents as the outputs of the adaptive model, the corresponding relations for the estimated currents are:

$$\hat{x} = \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix}, u = \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$
$$\hat{x}^{\bullet} = \hat{A}.\hat{x} + B.u + C \quad (6)$$

Where:

$$\hat{A} = \begin{bmatrix} -\frac{\hat{R}_s}{L_d} & \frac{L_q}{L_d}\omega_r \\ -\frac{L_d}{L_q}\omega_r & -\frac{\hat{R}_s}{L_q} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}, C = \begin{bmatrix} 0 \\ -\omega_r \frac{\psi_f}{L_q} \end{bmatrix} \quad (7)$$

Define the current errors as:

$$\varepsilon_d = i_d - \hat{i}_d$$
$$\varepsilon_q = i_q - \hat{i}_q \quad (8)$$

After some manipulations, the error state equations of the d-q currents can be derived and combined in a compact matrix form, as:

$$\begin{bmatrix} \dfrac{d\varepsilon_d}{dt} \\ \dfrac{d\varepsilon_q}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{\hat{R}_s}{L_d} & \dfrac{L_q}{L_d}\omega_r \\ -\dfrac{L_d}{L_q}\omega_r & -\dfrac{\hat{R}_s}{L_q} \end{bmatrix} \begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} + \dots \tag{9}$$

$$\begin{bmatrix} -\dfrac{1}{L_d} i_d \\ -\dfrac{1}{L_q} i_q \end{bmatrix} \left(R_s - \hat{R}_s\right)$$

The MRAS estimator is designed to estimate the value of stator resistance ($\hat{R}_s$). Define a candidate Lyapunov function as:

$$V = \tilde{x}^T \tilde{x} + \frac{1}{K_{R_S}} \tilde{R}_S^2 \tag{10}$$

It is obvious that V is positive definite.

We have:

$$\begin{Bmatrix} \tilde{i}_d = i_d - \hat{i}_d \\ \tilde{i}_q = i_q - \hat{i}_q \end{Bmatrix}$$

$$\tilde{x}^{\bullet} = Ax - \tilde{A}\tilde{x} = A\hat{x} + A\tilde{x} - \hat{A}\hat{x} = A\tilde{x} + \tilde{A}\hat{x} \tag{11}$$

$$\tilde{A} = A - \hat{A} = \begin{bmatrix} -\dfrac{\tilde{R}_s}{L_d} & 0 \\ 0 & -\dfrac{\tilde{R}_s}{L_q} \end{bmatrix}$$

Some manipulations are used to derive the derivate of the function V:

$$\begin{aligned} \dot{V} &= \dot{\tilde{x}}^T \tilde{x} + \tilde{x}^T \dot{\tilde{x}} + \frac{2}{K_{R_S}} \tilde{R}_S \dot{\tilde{R}}_S \\ \rightarrow \dot{V} &= \tilde{x}^T (A^T + A)\tilde{x} \dots \\ &+ \underbrace{\hat{x}^T \tilde{A}^T \tilde{x}}_{1} + \underbrace{\tilde{x}^T \tilde{A} \hat{x}}_{2} + \frac{2}{K_{R_S}} \tilde{R}_S \dot{\tilde{R}}_S \end{aligned} \tag{12}$$

The first RHS term is negative definite (N.D) due to the property of the matrix A. In order to guarantee negative definiteness of $\dot{V}$, the remaining terms are equated to zero. Parts (1) and (2) of equation (12) are simplified as follows:

$$\hat{x}^T \tilde{A}^T \tilde{x} = \dots = -\tilde{R}_S \left(\frac{\hat{i}_d \tilde{i}_d}{L_d} + \frac{\hat{i}_q \tilde{i}_q}{L_q}\right) \tag{13}$$

$$\tilde{x}^T \tilde{A} \hat{x} = \dots = -\tilde{R}_S \left(\frac{\hat{i}_d \tilde{i}_d}{L_d} + \frac{\hat{i}_q \tilde{i}_q}{L_q}\right) \tag{14}$$

Replacing the simplified expressions for parts (1) and (2) in the RHS of (12) yields:

$$\begin{aligned} \dot{V} &= \underbrace{\tilde{x}^T (A^T + A)\tilde{x}}_{N.D} - 2\tilde{R}_s \left(\frac{\hat{i}_d \tilde{i}_d}{L_d} + \frac{\hat{i}_q \tilde{i}_q}{L_q}\right) \dots \\ &+ \frac{2}{K_{R_S}} \tilde{R}_S \dot{\tilde{R}}_S \\ &\rightarrow \frac{d\tilde{R}_S}{dt} = K_{R_S} \left(\frac{\hat{i}_d \tilde{i}_d}{L_d} + \frac{\hat{i}_q \tilde{i}_q}{L_q}\right) \end{aligned} \tag{15}$$

Assuming the rate of change of the actual stator resistance to be negligible, it can be assumed constant in the time derivation process, therefore:

$$\tilde{R}_S = R_S - \hat{R}_S \rightarrow \frac{d\tilde{R}_S}{dt} \approx -\frac{d\hat{R}_S}{dt} \tag{16}$$

Also, noting the following simple relations:

$$\begin{aligned} \tilde{i}_d &= \varepsilon_d = i_d - \hat{i}_d \rightarrow \hat{i}_d = i_d - \tilde{i}_d \\ \tilde{i}_q &= \varepsilon_q = i_q - \hat{i}_q \rightarrow \hat{i}_q = i_q - \tilde{i}_q \end{aligned} \tag{17}$$

After replacement in equation (14), the estimation law is obtained as follows:

$$\frac{d\hat{R}_S}{dt} = -K_{R_S} \left(\frac{(i_d - \varepsilon_d)\varepsilon_d}{L_d} + \frac{(i_q - \varepsilon_q)\varepsilon_q}{L_q}\right) \tag{18}$$

The estimation scheme for the stator resistance is shown in Figure 4.

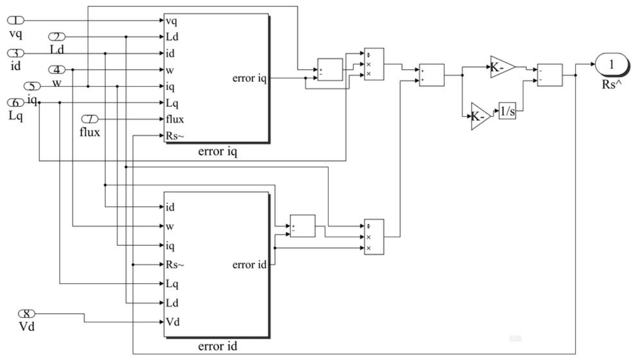

Figure 4. Stator resistance estimation scheme

Estimation of PM flux linkage

We can only use the q-axis voltage equation to estimate the PM flux linkage, because this axis only includes a term dependent on the PM flux linkage.

The dynamic equations for measured and estimated currents of q-channel are:

$$\begin{cases} \dot{i}_q = \dfrac{1}{L_q}(u_q - R_s i_q - \omega\psi_f - \omega L_d i_d) \\ \dot{\hat{i}}_q = \dfrac{1}{L_q}(u_q - R_s \hat{i}_q - \omega\hat{\psi}_f - \omega L_d i_d) \end{cases} \tag{19}$$

The error state equation for the q-channel can be derived as follows:

$$\dot{\tilde{i}}_q = -\frac{R_s}{L_q}\tilde{i}_q - \frac{\omega}{L_q}\tilde{\psi}_f \quad (20)$$

We propose the following Lyapunov function candidate:

$$V = \frac{1}{2}(\tilde{i}_q^{\,2} + \frac{1}{k}\tilde{\psi}_f^2) \quad (21)$$

The time derivative of this function is written as follows:

$$\dot{V} = \tilde{i}_q\dot{\tilde{i}}_q + \frac{1}{k}\tilde{\psi}_f\,\dot{\tilde{\psi}}_f$$
$$\rightarrow \dot{V} = \underbrace{(-\frac{R_s}{L_q}\tilde{i}_q^2)}_{N.D} - \frac{\omega\tilde{i}_q}{L_q}\tilde{\psi}_f + \frac{1}{k}\tilde{\psi}_f\,\dot{\tilde{\psi}}_f \quad (22)$$

The first RHS term being negative definite, to make this derivative negative definite, it suffices to equate the remaining terms of RHS to zero, leading to:

$$\dot{\tilde{\psi}}_f = K\frac{\omega}{L_q}\tilde{i}_q \quad (23)$$

Neglecting the time derivative of the actual PM flux linkage, the q-axis inductance is estimated as follows:

$$\dot{\hat{\psi}}_f \approx -K\frac{\omega}{L_q}\tilde{i}_q \quad (24)$$

The estimation scheme for the PM flux linkage is shown in Figure 5.

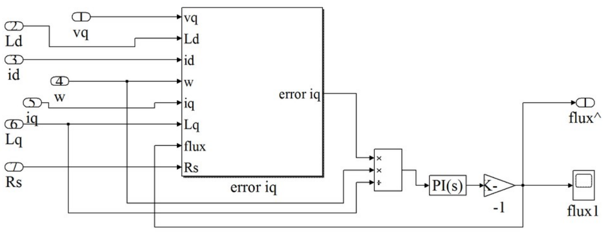

Figure 5. PM flux linkage estimation scheme

Estimation of d-axis inductance using Lyapunov-based MRAS

It is possible to use d-channel or q-channel voltage equations to design a law to estimate the d-axis inductance. For brevity, only the one based on the d-channel voltage equation is presented here. The dynamic equations for measured and estimated currents of d-channel are:

$$\begin{cases} \dot{i}_d = \frac{1}{L_d}(u_d - R_s i_d + \omega L_q i_q) \\ \dot{\hat{i}}_d = \frac{1}{\hat{L}_d}(u_d - R_s\hat{i}_d + \omega L_q i_q) \end{cases} ,\alpha_d \triangleq \frac{1}{L_d} \quad (25)$$

The error state equation for the q-channel can be derived as follows:

$$\dot{\tilde{i}}_d = \tilde{\alpha}_d(u_d + \omega L_q i_q) - R_s\,\alpha_d\,i_d + R_s\,\hat{\alpha}_d\,\hat{i}_d$$
$$\rightarrow \dot{\tilde{i}}_d = \tilde{\alpha}_d(u_d + \omega L_q i_q) - R_s\underbrace{(\alpha_d\,i_d - \hat{\alpha}_d\,\hat{i}_d)}_{\alpha_d\,\tilde{i}_d + \tilde{\alpha}_d\hat{i}_d} \quad (26)$$
$$\rightarrow \dot{\tilde{i}}_d = \tilde{\alpha}_d(u_d + \omega L_q i_q) - R_s\alpha_d\,\tilde{i}_d - R_s\tilde{\alpha}_d\,\hat{i}_d$$

We propose the following Lyapunov function candidate:

$$V = \frac{1}{2}(\tilde{i}_d^{\,2} + \frac{1}{k}\tilde{\alpha}_d^2) \quad (27)$$

The time derivative of this function is written as follows:

$$\dot{V} = \tilde{i}_d\dot{\tilde{i}}_d + \frac{1}{k}\tilde{\alpha}_d\dot{\tilde{\alpha}}_d \rightarrow \dot{V} = \underbrace{\tilde{i}_d(-R_s\alpha_d\tilde{i}_d)}_{N.D}...$$
$$+\tilde{i}_d\left(\tilde{\alpha}_d(u_d + \omega L_q i_q) - R_s\tilde{\alpha}_d\,\hat{i}_d\right)... \quad (28)$$
$$+\frac{1}{k}\tilde{\alpha}_d\dot{\tilde{\alpha}}_d$$

The first RHS term being negative definite, to make this derivative negative definite, it suffices to equate the remaining terms of RHS to zero, leading to:

$$\dot{\tilde{\alpha}}_d = -k(u_d + \omega L_q i_q - R_s\hat{i}_d)\tilde{i}_d \quad (29)$$

Neglecting the time derivative of the inverse of the actual d-axis inductance, the inverse of the d-axis inductance is estimated as follows:

$$\dot{\hat{\alpha}}_d = k(u_d + \omega L_q i_q - R_s\hat{i}_d)\tilde{i}_d \quad (30)$$

Estimation of q-axis inductance using Lyapunov-based MRAS

Similar to the d-axis inductance, both d-channel and q-channel equations can be used to derive the estimation law. The one incorporating the d-channel voltage equation is presented here. The dynamic equations for measured and estimated currents of d-channel are:

$$\begin{cases} \dot{i}_d = \frac{1}{L_d}(u_d - R_s i_d + \omega L_q i_q) \\ \dot{\hat{i}}_d = \frac{1}{L_d}(u_d - R_s\hat{i}_d + \omega\hat{L}_q i_q) \end{cases} \quad (31)$$

The error state equation for the d-channel can be derived as follows:

$$\dot{\tilde{i}}_d = -\frac{R_s}{L_d}\tilde{i}_d + \frac{\omega i_q}{L_d}\tilde{L}_q \quad (32)$$

We propose the following Lyapunov function candidate:

$$V = \frac{1}{2}(\tilde{i}_d^{\,2} + \frac{1}{k}\tilde{L}_q^2) \quad (33)$$

The time derivative of this function is written as follows:

$$\dot{V} = \tilde{i}_d \dot{\tilde{i}}_d + \frac{1}{k}\tilde{L}_q \dot{\tilde{L}}_q \rightarrow$$
$$\dot{V} = \underbrace{(-\frac{R_s}{L_d}\tilde{i}_d^{\,2})}_{N.D} + \frac{\omega i_q}{L_d}\tilde{i}_d \tilde{L}_q + \frac{1}{k}\tilde{L}_q \dot{\tilde{L}}_q \quad (34)$$

The first RHS term being negative definite, to make this derivative negative definite, it suffices to equate the remaining terms of RHS to zero, leading to:

$$\dot{\tilde{L}}_q = -K \frac{\omega i_q}{L_d}\tilde{i}_d \quad (35)$$

Neglecting the time derivative of the actual q-axis inductance, the q-axis inductance is estimated as follows:

$$\dot{\hat{L}}_q = K \frac{\omega i_q}{L_d}\tilde{i}_d \quad (36)$$

Simulation results

In order to validate the proposed estimation method, a PMSM with the electrical parameters in Table 1 [13] under vector control has been simulated using Matlab® Simulink. The overall simulation scheme is depicted in Figure 6.

Table 1. Electrical parameters the PMSM

Parameter	Value	Unit
R_a	2.85	Ohm
y_f	0.087	Wb
L_d	25	mH
L_q	26.5	mH

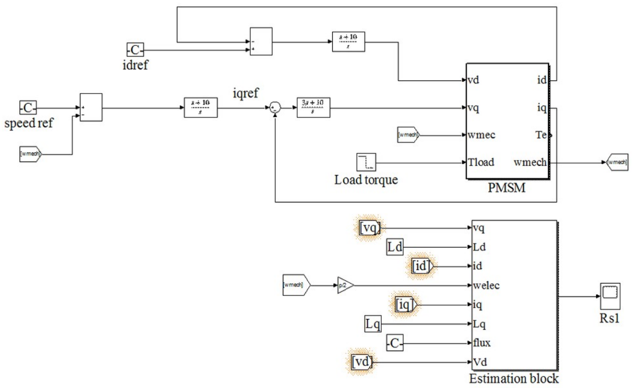

Figure 6. Overall system simulation scheme

In the simulations, the four electrical parameters (i.e. stator resistance, PM flux linkage and d-q inductances) have been estimated one by one. Although it is possible to estimate two parameters simultaneously due to two independent electrical equations, this is left for our future publications.

Figure 7 shows the actual and estimated values of the stator resistance. In order to investigate robustness of the estimation to changes in the resistance (due to heat effects, etc.), the value of the resistance has a stepwise change in the 2[nd] second. It is visible that the estimated resistance has tracked the actual resistance well.

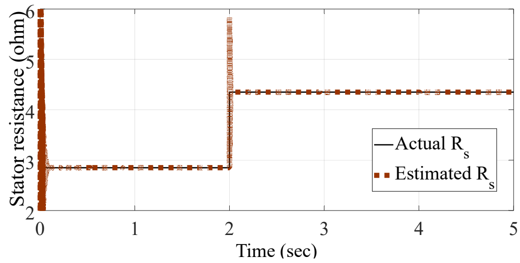

Figure 7. Estimated and actual stator resistances

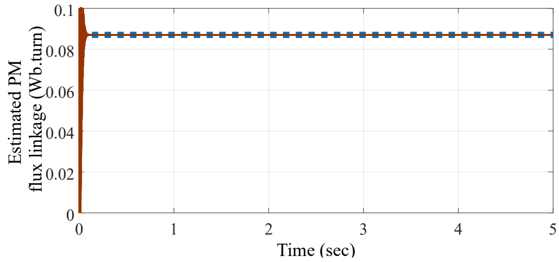

Figure 8. Estimated and actual PM flux linkages

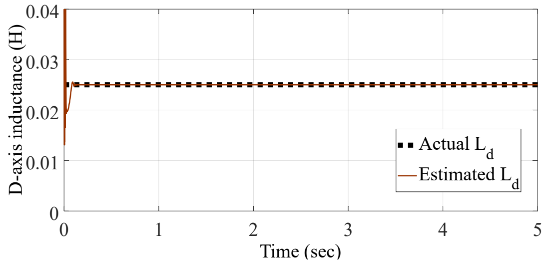

Figure 9. Estimated and actual d-axis inductances

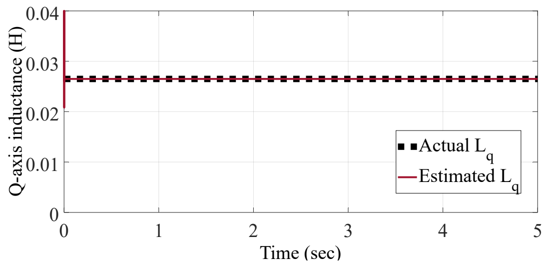

Figure 10. Estimated and actual q-axis inductances

Figures 8, 9 and 10 show respectively the estimations of PM flux linkage, d-axis inductance and q-axis inductance versus their respective actual values. It is clear that the proposed estimation scheme has acceptable performance with good dynamic response and no steady state error.

Conclusions

This paper proposed online estimation of electrical parameters of a PMSM using Lyapunov-based MRAS technique. The MRAS method is attractive from the practical point of view due to its simple implementation. The advantage of this kind of MRAS estimation is that the stability is theoretically guaranteed. It is possible to estimate two parameters at the same time, which will be included in subsequent papers. In addition, future work can consider more detailed PMSM models- leading to more accurate parameter estimations- by taking magnetic saturation and core losses into account. The estimation of all four electrical parameters is also a challenge due to rank-deficiency of the problem; this could be overcome by changing the operating point of the motor for an interval to estimate the remaining two parameters.

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