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Parameter estimation of permanent magnet stepper motors without mechanical sensors

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A R T I C L E I N F O

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A B S T R A C T

The paper presents a new sensorless parameter identification method for permanent magnet stepper motors. Current sensors are assumed available, but mechanical sensors are not. Data is obtained with open-loop commands at multiple speeds. A new frame is proposed that presents advantages similar to the d–q frame, but without the need for a position sensor. The method exploits derived linear parameterizations and least-squares algorithms. In some cases, overparameterization is resolved using elimination theory. The parameters identified using the new procedure are found to be very close to those obtained with sensors. The approach is potentially applicable to other types of synchronous motors.

1. Introduction

Permanent Magnet Stepper Motors (PMSMs) are widely used in industry for position control, especially in manufacturing applications. PMSMs are more robust than brush DC motors and produce high torque per volume. They are often controlled in open-loop, although the potential loss of synchronism limits operation away from resonances and from high acceleration trajectories. These problems can be resolved by using closed-loop control methods with position sensors of sufficient precision. Recent research has focussed on whether the performance of closed-loop control methods could be achieved using *sensorless* systems. In this case, sensorless refers to systems that do not have position sensors, although current sensors are still assumed to be available.

Sensorless control is useful to reduce the cost of the application, or when there is no space for a mechanical sensor. Current sensors can reconstruct the position of the rotor through the induced back-emf voltages at non-zero speeds (Johnson, Ehsani, & Guzelgunler, 1999; Schroedl, 2004; Shah, Espinosa-Pérez, Ortega, & Hilairet, 2011; Tomei & Verrelli, 2011). For such methods to succeed, the model of the motor and its parameters have to be well known, which brings to the forefront the question of parameter identification without position or velocity sensors, and notably an initial scenario for off-line parameter identification. Indeed, the electric motor manufacturers provide the parameters of the motor itself, without load. Moreover, these parameters are nominal, and therefore uncertain. Ultimately, sensorless identification could be used to provide auto-tuning of a sensorless control law, real-time adaptation, and fault detection.

The estimation of PMSM parameters was studied in Blauch, Bodson, and Chiasson (1993), Kim and Lorenz (2002), and Mobarakeh and Sargos (2001), but with rotor position information. Position sensorless identification was applied using special signals at standstill or under load condition in Nee, Lefevre, Thelin, and Soulard (2000), but for the identification of the d and q reactances only. Other methods to identify motor parameters online include Bolognani, Zigliotto, and Unterkofler (1997) and Lee, Jung, and Ha (2004), but Bolognani et al. (1997) only provides simulation results and in Lee et al. (2004), only the stator resistance and the back EMF constant are identified. In Ichikawa, Tomita, Doki, and Okuma (2004), Ichikawa, Tomita, Doki, and Okuma (2006), Yoshimi, Hasegawa, and Matsui (2010), parameter identification is realized in the d–q frame, where the position needed for the d–q transformation is estimated using identified parameters. This type of structure may be successful in practice, but guarantees of stability and convergence are absent, because parameter estimation depends on position estimation and vice versa.

This paper presents a new experimental off-line method for the identification of the parameters of a PMSM without position or velocity sensors, using open-loop command of the PMSM and assuming that the velocity is equal to the reference velocity on the average in steady-state, *i.e.*, that the motor synchronism is kept. Based on well-known parameter identification approaches such as the least squares algorithm and elimination theory, the

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contribution of this paper originates from a new change of variables leading to a frame of reference which is advantageous for sensorless applications. Compared to existing approaches, the method has the advantages of: identifying all of the electrical parameters as well as the mechanical parameters, deriving identification algorithms that are guaranteed to converge, validating the analytical results with experimental data. The results obtained without position sensors are compared to those obtained with sensors following the approach from Blauch et al. (1993). The theory is validated through experiments that were performed using a test bench available at the LAGIS laboratory at the École Centrale de Lille. The paper extends results presented at the *2012 American Control Conference* (Delpoux, Bodson, & Floquet, 2012). Compared to Delpoux et al. (2012), this paper provides a more extensive comparison of a method identifying the resistance based on the voltage equation to a method using the absorbed electrical power and the mechanical equation.

The article is divided into three parts. Section 2.1 presents the model of the PMSM in three different reference frames and the identification algorithms used in the paper. In Section 3, an identification procedure is developed for motors with position and velocity sensors, to be used as a basis for comparison. The last Section 4 presents the new identification procedure and the results obtained experimentally.

2. Preliminaries

2.1. PMSM model

In this section, the model of the PMSM is presented in three different frames, including a new frame that is particularly useful for sensorless applications. Fig. 1 shows the global scheme of the PMSM with the different variables used for identification. The different axes are represented in Fig. 2. For the purpose of off-line parameter identification, one assumes that all the parameters are constant. On-line parameter estimation can then be used to correct for variations, if necessary, but is not considered in this paper.

2.1.1. Model in the phase variables (a–b)

Eqs. (1) give the standard PMSM model in the phase (or winding) variables

$$\begin{cases} L\dfrac{di_a(t)}{dt} = v_a(t) - Ri_a(t) + K\Omega(t)\ \sin(N\theta(t)), \\ L\dfrac{di_b(t)}{dt} = v_b(t) - Ri_b(t) - K\Omega(t)\ \cos(N\theta(t)), \\ J\dfrac{d\Omega(t)}{dt} = K(i_b(t)\ \cos(N\theta(t)) - i_a(t)\ \sin(N\theta(t))) \\ \qquad\qquad - f_v\Omega(t) - C_r\ \mathrm{sgn}(\Omega(t)), \end{cases} \tag{1}$$

where v_a and v_b are the voltages applied to the two phases of the PMSM, i_a and i_b are the two phase currents, L is the inductance of a phase winding, R is the resistance of a phase winding, K is the back-EMF constant (and also the torque constant), θ is the angular position of the rotor, $\Omega = d\theta/dt$ is the angular velocity of the rotor,

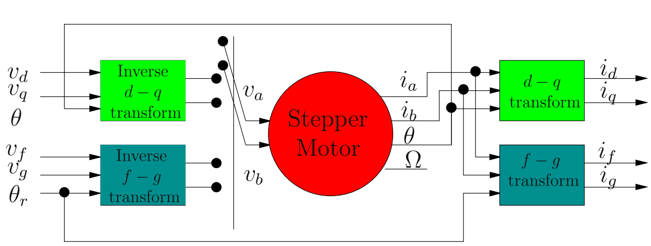

Fig. 1. Global scheme of the PMSM with *d–q* and *f–g* transformations.

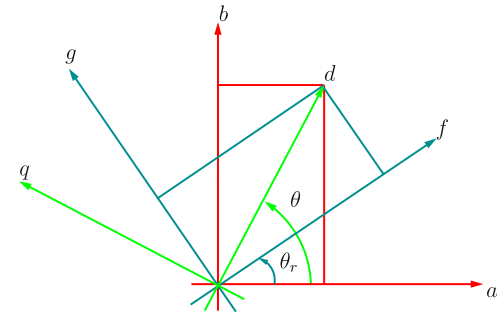

Fig. 2. Representation of variables in different reference frames.

N is the number of pole pairs (or rotor teeth), J is the moment of inertia of the rotor (including the load), f_v is the coefficient of viscous friction, and C_r is the coefficient of Coulomb friction.

2.1.2. Model in the rotating frame (d–q)

The phase model can be transformed using Park's transformation (Park, 1929):

$$[i_d, i_q]^T = M_p(\theta)[i_a, i_b]^T, \tag{2}$$

$$[v_d, v_q]^T = M_p(\theta)[v_a, v_b]^T, \tag{3}$$

where

$$M_p(\theta) = \begin{bmatrix} \cos(N\theta) & \sin(N\theta) \\ -\sin(N\theta) & \cos(N\theta) \end{bmatrix}. \tag{4}$$

Using this change of coordinates, the system (1) is transformed into the so-called d–q model

$$\begin{cases} L\dfrac{di_d(t)}{dt} = v_d(t) - Ri_d(t) + NL\Omega(t)i_q(t), \\ L\dfrac{di_q(t)}{dt} = v_q(t) - Ri_q(t) - NL\Omega(t)i_d(t) - K\Omega(t), \\ J\dfrac{d\Omega(t)}{dt} = Ki_q(t) - f_v\Omega(t) - C_r\ \mathrm{sgn}(\Omega(t)). \end{cases} \tag{5}$$

The d–q transformation is commonly used for PMSMs (and synchronous motors in general), because it results in constant voltages and currents at constant speed (instead of the high-frequency phase variables). Also, the model highlights the role of the quadrature current i_q in determining the torque. However, the d–q transformation is based on the position θ, which is not directly available in sensorless applications.

2.1.3. Model in the rotating reference frame (f–g)

The goal of this article is the identification of the parameters without the need for the position and the velocity. The d–q transformation is not suitable for such a purpose, given that the transformation $M_p(\theta)$ uses the position θ. To overcome the problem, a solution is to use the model in the phase variables to identify the parameters. However, the high frequencies of the phase variables at high speeds pose problems for the identification, in particular by making it difficult to filter out measurement noise.

In this article, a different frame is proposed that uses a reference position instead of the real position. The model in these variables is obtained using the transformation (2) and (3) but the Park matrix is defined as follows:

$$M_p(\theta_r) = \begin{bmatrix} \cos(N\theta_r) & \sin(N\theta_r) \\ -\sin(N\theta_r) & \cos(N\theta_r) \end{bmatrix}. \tag{6}$$