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Algebraic Identification Approach for Parameter Estimation in Surface-Mounted Permanent Magnet Synchronous Motors

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***Abstract*—In this paper, the problem of electrical and mechanical parameter estimation in Surface-Mounted Permanent Magnet Synchronous Motors (PMSMs) by means of the Algebraic Identification method is addressed. A complete identification methodology is proposed in two stages: the first stage addresses the identification of the electrical parameters, and the second stage tackles the identification of the mechanical parameters. Both stages are assisted by a model-free observer to estimate the angular speed of the PMSM. Three cases of simulation show that the algebraic identification method provides promising results to identify the electrical and mechanical parameters of the PMSM from the measurement of the currents i_d, i_q and the angular position θ.**

***Index Terms*—Algebraic Identification, Parameter Estimation, Permanent Magnet Synchronous Motors, PMSM, GPI Observer, Extended-state Observer, ESO.**

I. Introduction

Nowadays, Permanent Magnet Synchronous Motors (PMSMs) are one of the most commonly used motors in the industry due to their simple structure, small volume, low manufacturing cost, high torque and fast dynamic response. Nevertheless, the success of these motors in the wide ecosystem of industry applications is also due to the performance provided by the applied control method/scheme.

Under that scenario, many control schemes have been proposed in the literature, for instance: the analysis of a glass-handling robot actuated by PMSMs [1], or a manipulator robot whose controller was designed to optimize the energy consumption of the PMSMs [2]. On the other hand, advanced techniques for PMSMs such as: speed ripple suppression [3], robust nonlinear speed control with internal model [4], integral sliding mode control approach with disturbance observer to provide low-speed high-torque [5], or a MIMO sliding mode control approach via ESO-assistance for a robotic manipulator actuated by PMSMs [6], have also been recently investigated. But, most of these advances and improvements in speed and position control require reliable models of the PMSM. Although these new control proposals yield satisfactory results, it should be noted that these results are based or depend on some knowledge of the PMSM's electrical or mechanical parameters.

Thus, all the control strategies mentioned above are based on knowing the entire or part of the dynamic model of the PMSM, which demonstrates the importance of developing precise models through identification methods (see [7]). Several parameter identification techniques for PMSMs can be found in the literature, for example recursive least squares with a load observer [8], polynomial parameter identification [9], PSO-based algorithms [10], parameter identification based on the Newton iterative method [11], off-line self-learning identification methods for the electrical parameters [12] or identification algorithms with control schemes [13]. This paper addresses the parameter estimation problem of Surface-Mounted PMSMs by means of a different approach called Algebraic Identification (see [14], [15]) which has not been used to tackle this problem until now.

The algebraic identification methodology has been used to estimate parameters, states, signal derivatives, disturbances and also to detect faults [16]. Also, the algebraic technique makes it possible to face three fundamental obstacles in controller design tasks [14]: parameter identification, state estimation, and robustness with respect to classical additive disturbances. Regardless of the controller design technique, the algebraic technique can be adapted to the needs of any module-based control law, another feature that stands out is the basic invariant filtering for the treatment of noise effects, which is based on the noise attenuation properties of the integration operation. The algebraic identification method has already been compared to standard recursive identification algorithms, showing that unknown parameters are obtained in a substantially shorter period of time [15].

The main contributions of this work are listed as follows: a) proposing a step-by-step algebraic identification methodology to find the on-line estimator for the electrical and mechanical parameters of Surface-Mounted PMSMs, and b) defining a model-free observer to estimate the angular speed of the PMSM, which is used in combination with the parameter identification methodology.

The rest of this document is organized as follows. Section II presents the model of the PMSM. Subsequently, section III presents the formulation of the identification methodology.

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Section IV details the simulation results of the proposed methodology for parameter identification. Finally, the conclusions of this work and future research are presented in section V.

II. Dynamic Model of the PMSM

This document presents the algebraic identification methodology for Surface-Mounted PMSMs, therefore the electrical equations of the motor in the direction and quadrature (d-q) axis can be written as follows [17]:

$$v_d = Ri_d - \omega_e L i_q + L\frac{d}{dt}i_d, \tag{1}$$

$$v_q = Ri_q + \omega_e(Li_d + \Lambda_{pm}) + L\frac{d}{dt}i_q, \tag{2}$$

$$\omega_e = \frac{P}{2}\omega_r, \tag{3}$$

where R is the resistance, L is the inductance, Λ_{pm} is the flux linkage constant, P is number of pair poles, ω_e is the electrical speed, $\{i_d, i_q\}$ are the motor currents, v_d and v_q are the voltage inputs.

These electrical equations consider the following assumptions: a) In magnetic surface mounted machines, the inductances are approximately equal, for this reason equations (1) and (2) are expressed only in terms of L; and b) Taking into account that motor windings have a balanced load, it can be denoted that the phase resistances are equal.

The mechanical equations of the PMSM are defined as [17]:

$$\frac{d}{dt}\omega_r = \frac{1}{H}(T_{em} - sgn(\omega_r)J_o - b\omega_r - T_{load}) \tag{4}$$

$$T_{em} = K_t i_q \tag{5}$$

$$T_{em} = \frac{3P}{4}\Lambda_{pm} i_q \tag{6}$$

where H is a rotor inertia, J_o is the coulomb friction constant, b is viscous damping coefficient, K_t is the torque constant, ω_r is the mechanical speed of motor and T_{em} the electromagnetic torque.

III. Formulation of the Identification Methodology

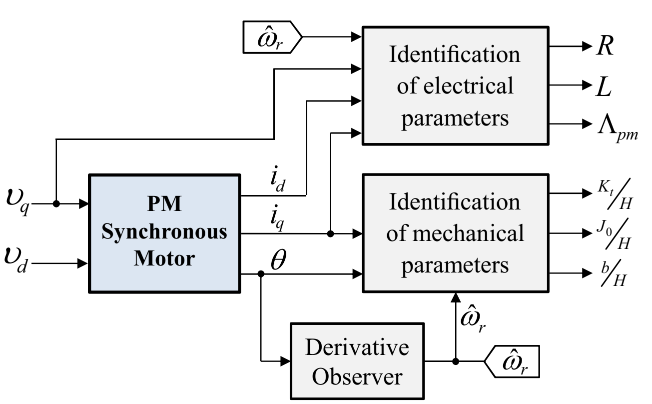

Fig. 1. General scheme of the proposed identification methodology.

The proposed algebraic identification methodology is performed through two stages (see Figure 1). In the first stage, the identification of the electrical parameters R, L and Λ_{pm} is developed. These estimations require both the measurements of the currents i_q and i_d, and the estimation of the angular speed ω_r. The second stage consists of identifying the parameters of the mechanical part of the motor $\frac{K_t}{H}$, $\frac{J_o}{H}$ and $\frac{b}{H}$. In this case, the measurement of i_q and θ are required along-with the estimation of ω_r. In both stages, an observer is proposed to provide accurate estimations of ω_r.

A. Identification of the electrical parameters

When analyzing the electrical equations of the PMSM, it can be corroborated that only two parameters, R and L, can be estimated from equation (1); for this reason it is convenient to propose the algebraic estimation algorithm based on equation (2) to estimate all electrical parameters.

Considering that the only measured variables for the identification of these parameters is the current i_q and i_d, the equation (2) must be multiplied by t and then integrated only once for the purpose of eliminating dependence of i_q on the initial conditions:

$$v_q t = Rti_q + t\omega_e(Li_d + \Lambda_{pm}) + Lt\frac{d}{dt}i_q$$

$$\int tv_q = R\int ti_q + L\left[\int t\omega_e i_d + \int t\frac{d}{dt}i_q\right] + \Lambda_{pm}\int t\omega_e$$

$$\int tv_q = R\int ti_q + L\left[\int t\omega_e i_d + ti_q - \int i_q\right] + \Lambda_{pm}\int t\omega_e. \tag{7}$$

Since there are three parameters to be estimated, it is necessary to integrate two more times to obtain a linear function (3×3 equation system) with respect to the set of unknown electric parameters (R, L and Λ_{pm}):

$$\int^{(2)} tv_q = R\int^{(2)} ti_q + L\left[\int^{(2)} t\omega_e i_d + \int ti_q - \int^{(2)} i_q\right] + \Lambda_{pm}\int^{(2)} t\omega_e, \tag{8}$$

$$\int^{(3)} tv_q = R\int^{(3)} ti_q + L\left[\int^{(3)} t\omega_e i_d + \int^{(2)} ti_q - \int^{(3)} i_q\right] + \Lambda_{pm}\int^{(3)} t\omega_e, \tag{9}$$

$$P_e(i_q, i_d, \omega_e)\begin{bmatrix} R \\ L \\ \Lambda_{pm}\end{bmatrix} = q_e(v_q)$$

with $P(i_q, i_d, \omega_e)$ and $q(v_q)$ given by:

$$P_e = \begin{bmatrix} P^e_{11} & P^e_{12} & P^e_{13} \\ P^e_{21} & P^e_{22} & P^e_{23} \\ P^e_{31} & P^e_{32} & P^e_{33} \end{bmatrix} \qquad q_e = \begin{bmatrix} q^e_1 \\ q^e_2 \\ q^e_3 \end{bmatrix}$$

where

$$P_e = \begin{bmatrix} \int ti_q & \int t\omega_e i_d + ti_q - \int i_q & \int t\omega_e \\ \int^{(2)} ti_q & \int^{(2)} t\omega_e i_d + \int ti_q - \int^{(2)} i_q & \int^{(2)} t\omega_e \\ \int^{(3)} ti_q & \int^{(3)} t\omega_e i_d + \int^{(2)} ti_q - \int^{(3)} i_q & \int^{(3)} t\omega_e \end{bmatrix}$$

$$q_e = \begin{bmatrix} \int v_q \\ \int^{(2)} v_q \\ \int^{(3)} v_q \end{bmatrix}.$$

For the estimation of the electrical parameters, both sides of the equation must be pre-multiplied by the inverse of P_e, obtaining:

$$\begin{bmatrix} R \\ L \\ \Lambda_{pm} \end{bmatrix} = [P_e]^{-1} * q_e,$$

in which, for a time t from $[0, \epsilon)$ where $\epsilon = 0.4s$, the parameters take an arbitrary value; for $t > \epsilon$, the parameters R, L and Λ_{pm} take the value of the estimator, thus:

$$\begin{bmatrix} R \\ L \\ \Lambda_{pm} \end{bmatrix} = \begin{cases} Arbitrary & for \quad t \in [0, \epsilon) \\ P_e^{-1} * q_e & for \quad t \in [\epsilon, +\infty] \end{cases}$$

As the electric speed ω_e is needed to estimate the electric parameters, it is essential to know the number of pole pairs P and estimate ω_r. This estimate will be explained in detail in section III-C.

B. Identification of the mechanical parameters

For estimating the mechanical parameters. This system must be independent of the initial conditions of the plant, independent of the disturbance and must also be based solely on the knowledge of the signals i_q , θ and the estimation of ω_r. Taking into consideration that $\omega_r = \dot{\theta}$ equation (4) can be expressed as follows:

$$\ddot{\theta} = \frac{K_t}{H} i_q - \frac{J_o}{H} sgn(\omega_r) - \frac{b}{H}\dot{\theta},$$

multiplying by t^2 on both sides of the equation, the dependence of the initial conditions is eliminated:

$$\ddot{\theta}t^2 = \frac{K_t}{H} i_q t^2 - \frac{J_o}{H} sgn(\omega_r)t^2 - \frac{b}{H}\dot{\theta}t^2,$$

likewise it is possible to parameterize the equation as a function of θ by means of two iterated integrals:

$$\int \ddot{\theta}t^2 = \frac{K_t}{H}\int i_q t^2 - \frac{J_o}{H}\int sgn(\omega_r)t^2 - \frac{b}{H}\int \dot{\theta}t^2$$

$$t^2\dot{\theta} - 2\int t\dot{\theta} = \frac{K_t}{H}\int i_q t^2 - \frac{J_o}{H}\int sgn(\omega_r)t^2 - \frac{b}{H}\left[t^2\theta - 2\int t\theta\right]$$

$$\theta t^2 - 4\int t\theta + 2\int^{(2)} \theta = \frac{K_t}{H}\int^{(2)} i_q t^2 - \frac{J_o}{H}\int^{(2)} sgn(\omega_r)t^2 - \frac{b}{H}\left[\int t^2\theta - 2\int^{(2)} t\theta\right].$$

Then, in order to obtain a linear function (3×3 equation system) with respect to the set of parameters K_t/H, J_o/H and b/H, an additional double integration is applied:

$$P_m(t, \theta, i_q, \omega_r)\begin{bmatrix} K_t/H \\ J_o/H \\ b/H \end{bmatrix} = q_m(t, \theta)$$

where the matrix $P(t, \theta, i_q, \omega_r)$ and $q(t, \theta)$ are given by:

$$P_m = \begin{bmatrix} P^m_{11} & P^m_{12} & P^m_{13} \\ P^m_{21} & P^m_{22} & P^m_{23} \\ P^m_{31} & P^m_{32} & P^m_{33} \end{bmatrix} \qquad q_m = \begin{bmatrix} q^m_1 \\ q^m_2 \\ q^m_3 \end{bmatrix}$$

with

$$P^m_{11} = \int^{(2)} i_q t^2$$

$$P^m_{12} = -\int^{(2)} sgn(\omega_r)t^2$$

$$P^m_{13} = -\int t^2\theta + 2\int^{(2)} t\theta$$

$$P^m_{21} = \int^{(3)} i_q t^2$$

$$P^m_{22} = -\int^{(3)} sgn(\omega_r)t^2$$

$$P^m_{23} = -\int^{(2)} t^2\theta + 2\int^{(3)} t\theta$$

$$P^m_{31} = \int^{(4)} i_q t^2$$

$$P^m_{32} = -\int^{(4)} sgn(\omega_r)t^2$$

$$P^m_{33} = -\int^{(3)} t^2\theta + 2\int^{(4)} t\theta$$

$$q^m_1 = \theta t^2 - 4\int t\theta + 2\int^{(2)} \theta$$

$$q^m_2 = \int \theta t^2 - 4\int^{(2)} t\theta + 2\int^{(3)} \theta$$

$$q^m_3 = \int^{(2)} \theta t^2 - 4\int^{(3)} t\theta + 2\int^{(4)} \theta$$

It can be seen that the matrix P_m and q_m are singular in time equal to zero, however the matrix P_m is invariant in a time t from $[0, \epsilon)$ where $\epsilon = 0.4s$, in this time interval the parameters take an arbitrary value, for $t > \epsilon$, the parameters

K_t/H, J_o/H and b/H, in this time interval take value of the estimate:

$$\begin{bmatrix} K_t/H \\ J_o/H \\ B/H \end{bmatrix} = \begin{cases} Arbitrary & for \quad t \in [0, \epsilon) \\ \\ P_m^{-1} * q_m & for \quad t \in [\epsilon, +\infty] \end{cases}$$

C. Derivative Observer

Since ω_r is an unmeasured state required for the algebraic identification of the PMSM parameters, the following state observer is proposed. Consider the following internal model approximation for the signal θ defined as $\ddot{\theta} = 0$, where its state-space representation takes the form:

$$\begin{aligned} \dot{x} &= Ax \\ y &= Cx, \end{aligned} \tag{10}$$

where, $x_1 = y = \theta$, $x_2 = \dot{\theta}$, $x_3 = \ddot{\theta}$, $x = [x_1, x_2, x_3]^T$ is the state vector and the matrices A and C are given by,

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}.$$

Based on the system (10), the following observer is proposed to provide accurate estimations of $\omega_r = \dot{\theta}$:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + L_o(y - \hat{y}), \quad \hat{y} = C\hat{x} \\ \dot{\hat{x}} &= (A - L_oC)\hat{x} + L_oy \end{aligned}$$

where L_o is the observer gain that establishes the dynamics for the observer. Then the state-space matrices of the observer to provide the required estimation are:

$$A_{obs} = [A - L_oC], \quad B_{obs} = [L_o],$$
$$C_{obs} = [0 \quad 1 \quad 0], \quad D_{obs} = [0],$$

where the C_{obs} matrix corresponds to the estimated state $\hat{\omega}_r$.

In order to obtain an estimate of ω_r according to the desired bandwidth, the observer gain L_o is designed to place the eigenvalues of the matrix A_{obs} at $[-200, -250, -300]$.

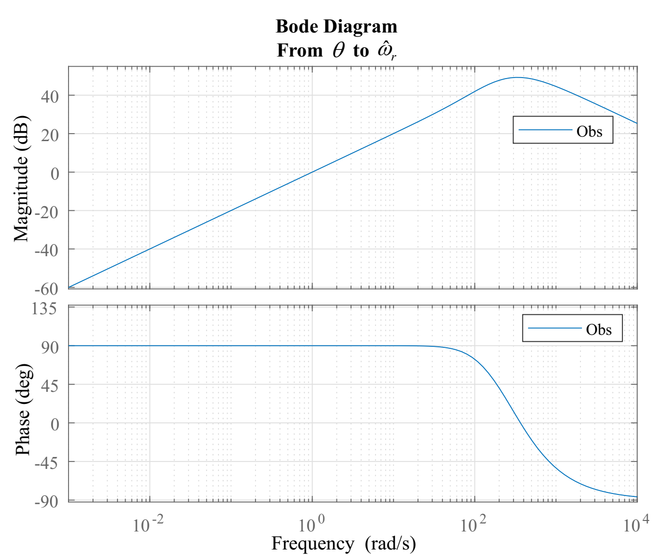

Fig. 2. Observer Bode diagram from θ to $\hat{\omega}_r$.

Figure 2 represents the bode diagram from θ to $\hat{\omega}_r$ of the observer, which shows a desired behavior of the estimation within the selected bandwidth. Notice that the observer reduces noise at high frequencies as opposed to a pure derivative which amplifies the magnitude of the measurement noise.

IV. Numerical Results and Discussion

In order to validate the proposed algebraic identification methodology for estimation of the electrical and mechanical parameters of the PMSM, Matlab/simulink simulation software is used and configured with the fixed-Step Bogacki-Shampine simulation method using a time-step of $T_s = 0.001s$ to ensure a good enough sampling of all signals.

Subsequently, three different identification cases are selected which are intended to verify the proposed estimation methodology. Table I details all PMSM parameters for each case:

TABLE I
PMSM parameters for cases 1, 2 and 3.

Parameter	Case 1	Case 2	Case 3	Unit
P	10	8	12	- - -
Λ_{pm}	0.0122	0.0232	0.0052	V s
R	0.10389	0.25393	0.9898	Ω
L	$2.096 \cdot 10^{-4}$	$3.196 \cdot 10^{-4}$	$6.796 \cdot 10^{-3}$	H
K_t	0.0903	0.1392	0.0468	Nm/A
J_0	0.0213	0.103	0.0215	Nm
b	$1.676 \cdot 10^{-4}$	$1.999 \cdot 10^{-4}$	$2.292 \cdot 10^{-4}$	Nms
H	$5.347 \cdot 10^{-3}$	$6.847 \cdot 10^{-3}$	$2.447 \cdot 10^{-3}$	Kgm^2

The two-stage identification process requires the estimation of ω_r and the measurement of currents i_d, i_q, to identify the electrical parameters R, L and Λ_{pm}.

Parameter estimations converge within a time less than 1 sec. In the case of the identification of the mechanical parameters, the measurement of i_q and , the rotor position θ are required, but also requires the estimation of ω_r that is obtained by the proposed observer. With the purpose of analyzing the transient of each estimated parameter ϵ is set to $\epsilon = 0.01s$. All results of estimation for each case are shown in Figure 3. Notice that the inertia H of the motor is combined with the value of the identified mechanical parameters.

The estimation errors obtained by the algebraic identification methodology expressed as percentage deviations from the nominal/real values are described in the following table:

TABLE II
Estimation error (%) of PMSM parameters for cases 1, 2 and 3.

Parameter	Case 1 (%)	Case 2 (%)	Case 3 (%)
Λ_{pm}	0.0012	0.0431	0.15
R	0.1904	0.1575	0.0101
L	0.0476	0.0156	0.0294
K_t/H	0.0032	0.0020	0.0052
J_0/H	0.0026	0.0010	0.0011
b/H	0.0051	0.0025	0.0029

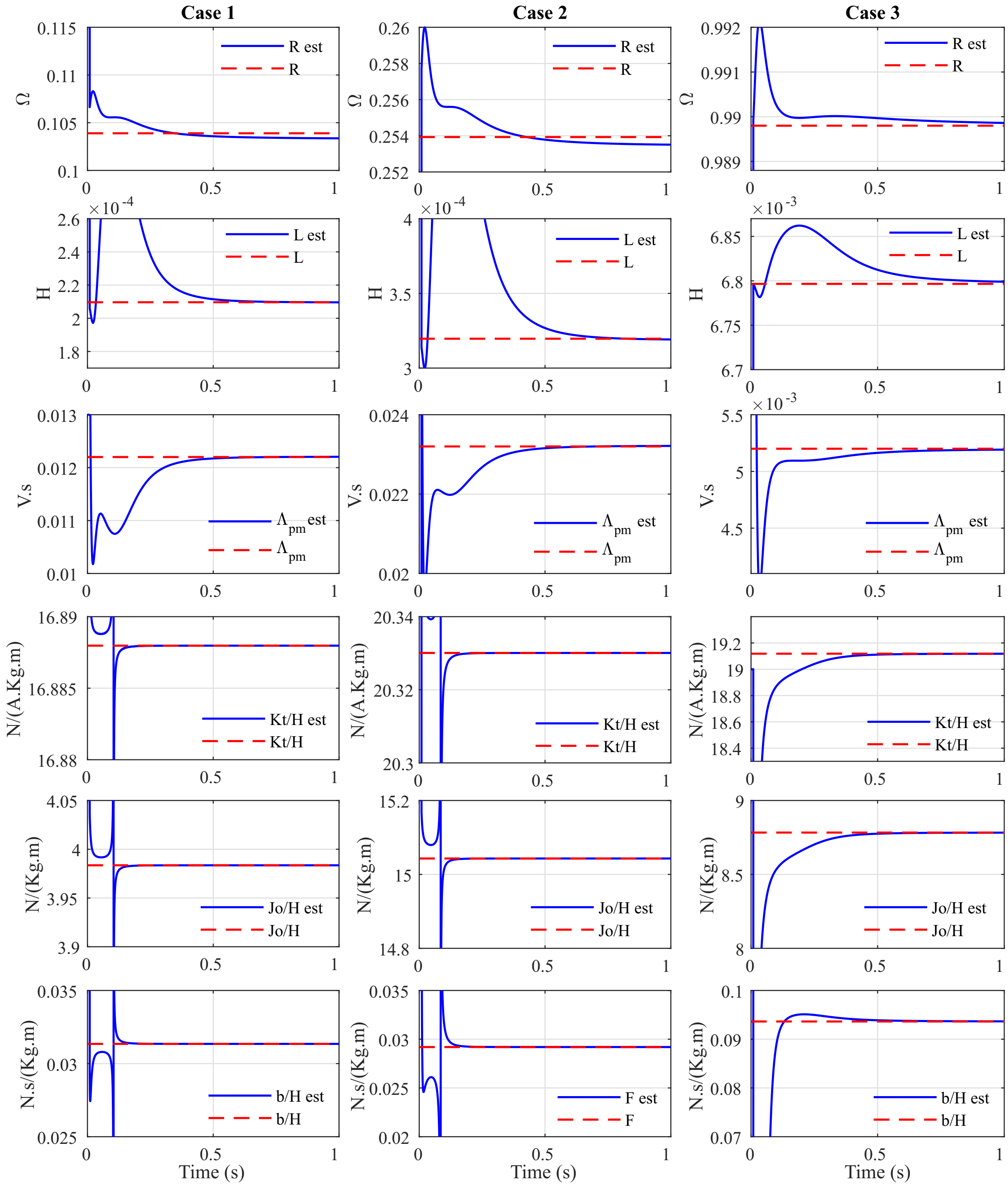

Fig. 3. Evolution and convergence of each estimated parameter for study cases 1, 2 and 3.

V. Conclusions

In this article, the identification of the electrical and mechanical parameters for surface mounted permanent magnet synchronous motors was achieved by proposing a two-stage algebraic identification methodology. The proposed methodology is based on the d-q model of the PMSM without any applied control scheme, and requires the measurement of the currents i_d, i_q and the angular position θ. An observer to estimate the mechanical speed of the motor $\hat{\omega}_r$ was also proposed and combined with the identification scheme to provide a reasonable estimation of $\hat{\omega}_r$ in terms of noise reduction at high frequencies and estimation performance. The simulation results show that the parameters converge to the required value in a short period of time. For future research, the methodology to identify parameters of the PMSM will be adapted and extended for PMSMs working in closed loop, e.g. torque/velocity/position.

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