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A New Approach on Stator Flux Estimation of IPMSMs Considering Magnetic and Cross-Coupling Saturations ⋆

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Abstract: This paper deals with estimating the stator flux of interior permanent magnet synchronous machines (IPMSMs) for hybrid electric vehicles (EHV) applications. The magnetic uncertainties due to the magnetic saturation are considered as new terms on the current-flux model of the machine. Considering the new model, an appropriate observer based on extended Kalman like algorithm is proposed to observe those terms. The observed terms are then used on the flux estimator to take into account the effect of magnetic saturation. The observability and the stability of the observer for the proposed system are studied. The simulation and experimental results are presented to illustrate the capacities of the proposed method.

Keywords: IPMSM, parameter estimation, stator flux estimator, inductance estimation, saturation, Kalman-like observer.

1. INTRODUCTION

The electric vehicles and hybrid electric vehicles (EV/HEV) are being more and more popular for car companies. Different types of electric motor have been investigated to be used as the motor of traction of these vehicles. The interior permanent magnet synchronous machines (IPMSMs) with specific features such as simplicity, reliability and robustness have been one of the best choices for this application. In the last two decades, it has been tried to eliminate the captures as much as possible for drive systems, particularly position and torque sensors which are bulky and expensive. Therefore, designing observers based on the model of machine and/or based on the output signals have been more and more paid attention. Adequate works have been perofrmed in sensorless drives where the rotor position is estimated. Recently, the torque estimation has been also being an interest for drive manufactures.

Regarding the model of an IPMSM, the electromagnetic torque can be properly estimated when the flux linkages are available in presence of measured currents. Based on the proposed methods in the literature, the flux of an IPMSM can be estimated based on two model known as voltage model and current model. The voltage model is the definition of Farady law when the flux is obtain by the integral of electromotive force (EMF) (Holtz, 2002). There are some inconveniences for this type of estimation such as the lack of observability at standstill and the creation of an offset in the estimated flux due to unknown initial condition of open-loop integrator (Holtz and Juntao Quan, 2003). In order to solve the latter problem, some filters have been proposed to be accompanied with the integrator (Koteich, 2016; Feng et al., 2017). However, the observability problem is still the main challenge of this type of estimation. The current model has been identified as the relation between flux and currents of the machine. This relationship is really nonlinear but can be simplified as a linear model based on the magnetic parameters known as inductances and permanent magnet flux. Any nonlinearity in the model and also the variation of inductances due to magnetic saturation even in the linear models induces an error between the real flux and the estimated one. It has been proposed in the literature to estimate the permanent magnet flux by an extended Kalman filter (Xiao et al., 2010) and the inductances (Hamida et al., 2013; Tinazzi and Zigliotto, 2015; Martinez et al., 2018; Wang et al., 2019) by different types of signal- and model-based observers to improve the performance of current model flux estimator. In (Hamida et al., 2013), two nonlinear interconnected observers was proposed to estimate stator resistance, linear inductance, load torque and rotor speed based on the model of a surface PMSM without considering the variation of magnetic saturation during the motor operation. A torque estimator based on current-flux model was presented in (Tinazzi and Zigliotto, 2015) for high speed operation. The coupling-effect between d, and q flux were taken into account and the approach was experimentally verified at constant speed 1000 rpm. A torque estimator was also proposed by (Martinez et al., 2018) where the inductances of IPMSM, neglecting the coupling-effect inductance, were estimated based on high frequency injection method. The coupling-effect inductance was taken into account in (Wang et al., 2019) to be estimated by high frequency injection method. However,

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the effect of non-linearity due to the magnetic saturation in the model of estimation is not taken into account.

In this paper, a flux/torque estimator based on current model is proposed. The effect of magnetic saturation on flux estimator including the coupling-effect is investigated and taken into account to propose a new model for IPMSM. Regarding the model which includes some terms related to the magnetic uncertainties, an adaptive observer known as extended Kalman like observer is designed for the proposed model. The observer estimates the uncertainty terms on the model by using measured currents. The observability and stability analysis of the observer for the proposed model are investigated and the results are shown for a range of rotor speed including zero speed crossing and zero speed standing.

2. MODEL OF IPMSM

2.1 Saturated Model of IPMSM

Model of an IPMSM in rotating synchronous reference frame (dq) can be represented in (1)-(3) by taking into account the saturation functions. It is supposed that the magnet flux is constant and sufficiently aligned in d-axis.

$$\begin{cases} \dfrac{\mathrm{d}\varphi_d}{\mathrm{d}t} = v_d - R_s i_d + \omega_e \varphi_q \\ \dfrac{\mathrm{d}\varphi_q}{\mathrm{d}t} = v_q - R_s i_q - \omega_e \varphi_d - \omega_e \phi_f \end{cases} \quad (1)$$

$$\begin{cases} i_d = \dfrac{\varphi_d}{L_{d0}} + \underbrace{3k_1\varphi_d^2 + k_2\varphi_q^2 + 4k_3\varphi_d^3 + 2k_4\varphi_d\varphi_q^2}_{f_{sat-d}} \\ i_q = \dfrac{\varphi_q}{L_{q0}} + \underbrace{2k_2\varphi_d\varphi_q + 2k_4\varphi_d^2\varphi_q + 4k_5\varphi_q^3}_{f_{sat-q}} \end{cases} \quad (2)$$

$$T_e = \underbrace{1.5p(\phi_f i_q)}_{T_{pm}} + \underbrace{1.5p(\varphi_d i_q - \varphi_q i_d)}_{T_{rel}} \quad (3)$$

where $R_s, L_{d0}, L_{q0}, \omega_e, \phi_f$ and p are stator resistance, linear d-axis stator inductance, linear q-axis stator inductance, angular synchronous speed, permanent magnet flux and number of pole pair, respectively. The terms f_{sat} represent an example of magnetic saturation functions that can be determined in the rotating synchronous reference frame. The variables v, i, φ and T represent stator voltage, stator current, stator flux generated by stator currents, and electromagnetic torque, respectively. Electromagnetic torque in (3) is divided into two terms known as permanent magnet torque (T_{pm}) and reluctance torque (T_{rel}). Furthermore, the total flux linkage of an IPMSM in the dq frame can be determined by (4).

$$\begin{cases} \lambda_d = \phi_f + \varphi_d \\ \lambda_q = \varphi_q. \end{cases} \quad (4)$$

For an IPMSM, the stator fluxes generated by stator currents, the electromagnetic torque and the total flux vectors can be estimated by (2), (3) and (4), respectively, in presence of measured currents. For a precise estimation, the right values of the magnetic parameters in the model including the permanent magnet flux (ϕ_f), the linear inductances (L_{d0}, L_{q0}) and the saturation coefficients (k_1 to k_5) are mandatory. Any uncertainties in these parameters make an error between the real flux/torque and the estimated ones. Furthermore, the proposed saturation functions in (2) may change for different motors.

2.2 Proposed Model of IPMSM Considering Magnetic Saturation Uncertainties

The aim of this model is to consider the uncertainties on the linear inductances and the magnetic saturations functions. For this, a set of new variables known as g_d and g_q are introduced as (5).

$$\begin{cases} g_d = f_{sat-d} + (\Delta L^{-1}_{d_0})\varphi_d + \Delta f_{sat-d} \\ g_q = f_{sat-q} + (\Delta L^{-1}_{q_0})\varphi_q + \Delta f_{sat-q} \end{cases} \quad (5)$$

with:

$$\begin{cases} \Delta L_{d0}^{-1} = \dfrac{1}{L_{d0m}} - \dfrac{1}{L_{d0}}, \Delta L_{q0}^{-1} = \dfrac{1}{L_{q0m}} - \dfrac{1}{L_{q0}} \\ \Delta f_{sat-dq} = f_{sat-(dq)m} - f_{sat-(dq)} \end{cases} \quad (6)$$

where, L_{d0m}, L_{q0m}, and $f_{sat-(dq)m}$ are the exact values of the linear coefficients between fluxes and currents and the real saturation function for the machine, respectively, while $\Delta L^{-1}_{d_0}$, $\Delta L^{-1}_{q_0}$ and Δf_{sat-dq} represent the deviations between real and first analytical evaluation of those parameters.

By taking into account the proposed variables g_d and g_q in (1)-(2), and rewriting the equations based on current stators as state variables, a new model which represents the uncertainties due to magnetic saturation is obtained as (7). Then, the stator fluxes generated by stator currents and total flux vectors are obtained as (8) and (9), respectively. The unknown variables g_d and g_q can be estimated by an observer based on the model (7).

$$\begin{cases} \dfrac{\mathrm{d}i_d}{dt} = -\dfrac{R_s}{L_{d0}} i_d + \dfrac{\omega_e L_{q0}}{L_{d0}} i_q - \dfrac{\omega_e L_{q0}}{L_{d0}} g_q + \dfrac{v_d}{L_{d0}} + \dfrac{\mathrm{d}g_d}{dt} \\ \dfrac{\mathrm{d}i_q}{dt} = -\dfrac{R_s}{L_{q0}} i_q - \dfrac{\omega_e L_{d0}}{L_{q0}} i_d + \dfrac{\omega_e L_{d0}}{L_{q0}} g_d + \dfrac{v_q - \omega_e \phi_f}{L_{q0}} + \dfrac{\mathrm{d}g_q}{dt}. \end{cases} \quad (7)$$

$$\begin{cases} \varphi_d = L_{d0}(i_d - g_d) \\ \varphi_q = L_{q0}(i_q - g_q). \end{cases} \quad (8)$$

$$\begin{cases} \lambda_d = \phi_f + L_{d0}(i_d - g_d) \\ \lambda_q = L_{q0}(i_q - g_q). \end{cases} \quad (9)$$

It should be noted that, the model can be also used for reluctance synchronous reluctance motor (SynRM) by considering permanent magnet flux (ϕ_f) equal to zero.

3. STATOR FLUX OBSERVER

A new state variable system considering i_d, i_q, g_d and g_q as state variables and stator currents as output variables are introduced in (10)-(12). The rotor speed is considered as an input for the system. For an IPMSM drive for EHV applications which is commanded by a reference torque demanded by driver, the reference current in q-axis is not sharply changed and the d-axis reference current is constant. Any slowly changes in stator currents amplitude (dq rerefrece currents), makes the slowly changes for magnetic saturation functions in dq frame which are a function of those currents. Thus, it is assumed that the variables g_{dq}

vary slowly and their first derivative can be set to zero. Then the following system can be established.

$$\begin{cases} \dot{x}(t) = f(x(t), u(t)) \\ y(t) = h(x(t)) \end{cases} \tag{10}$$

with:

$$x = (i_d, i_q, g_d, g_q)^T, u = (v_d, v_q, \omega_e)^T, y = (i_d, i_q)^T. \tag{11}$$

$$f(x,u) = \begin{cases} -\frac{R_s}{L_{d0}} i_d + \frac{\omega_e L_{q0}}{L_{d0}} i_q - \frac{\omega_e L_{q0}}{L_{d0}} g_q + \frac{v_d}{L_{d0}} \\ -\frac{R_s}{L_{q0}} i_q - \frac{\omega_e L_{d0}}{L_{q0}} i_d + \frac{\omega_e L_{d0}}{L_{q0}} g_d + \frac{v_q - \omega_e \phi_f}{L_{q0}} \\ 0 \\ 0 \end{cases} \tag{12}$$

3.1 Observability study

The locally weakly observability of the proposed system (10)-(12), based on the rank criterion are investigated in this part (Hermann and Krener, 1977). The local observability of the system is satisfied if the regularly observability matrix $O_y(x)$ is full rank at x_0. For a 4th-order system, $O_y(x)$ is given in (13).

$$O_y(x) = \frac{\partial}{\partial x} \begin{pmatrix} \pounds_f^0 h(x) \\ \pounds_f^1 h(x) \\ \pounds_f^2 h(x) \\ \pounds_f^3 h(x) \end{pmatrix} = \frac{\partial}{\partial x} \begin{pmatrix} h(x) \\ \frac{\partial h(x)}{\partial x} f(x) \\ \frac{\partial \pounds_f^1 h(x)}{\partial x} f(x) \\ \frac{\partial \pounds_f^2 h(x)}{\partial x} f(x) \end{pmatrix} \tag{13}$$

where $\pounds_f^k h(x)$ is the k_{th}-order *Lie derivative* of the function h with respect to the vector field f. After the computation of O_y for the proposed system (10)-(12), it is found that there are no linear combination between the rows and the columns of the matrix for $\omega_e \neq 0$. Let us set $\omega_e = 0$, then, the observability matrix is obtained as:

$$O_y(x) = \begin{pmatrix} 1 & 0 & -\frac{R_s}{L_{d0}} & 0 & \frac{R_s^2}{L_{d_0}^2} & 0 & \frac{-R_s^3}{L_{d_0}^3} & 0 \\ 0 & 1 & 0 & -\frac{R_s}{L_{q0}} & 0 & \frac{R_s^2}{L_{q_0}^2} & 0 & \frac{-R_s^3}{L_{q_0}^3} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T \tag{14}$$

Thus, obviously the observability of the proposed system cannot be established at null speed operation even if the higher derivatives of measures (currents) are used. As a conclusion of the observability analysis, the locally weakly observability of the system is guaranteed for nonzero speeds.

3.2 Observer Design

Extended Kalman like observer for the proposed model: Regarding the system presented in (10)-(12), an observer is designed for the system based on Extended Kalman Like algorithm with the rotor speed as an input for the matrix A. The observer system is describes in (15).

$$\begin{cases} \dot{\hat{x}} = A(\omega_e)\hat{x} + v(\omega_e, v_{dq}) - K(C\hat{x} - y) \\ \hat{y} = C\hat{x} \end{cases} \tag{15}$$

with:

$$A(\omega_e) = \begin{pmatrix} -\frac{R_s}{L_{d0}} & \frac{\omega_e L_{q0}}{L_{d0}} & 0 & -\frac{\omega_e L_{q0}}{L_{d0}} \\ -\frac{\omega_e L_{d0}}{L_{q0}} & -\frac{R_s}{L_{q0}} & \frac{\omega_e L_{d0}}{L_{q0}} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{16}$$

$$v = \begin{pmatrix} \frac{v_d}{L_{d0}} & \frac{v_q - \omega_e \phi_f}{L_{d0}} & 0 & 0 \end{pmatrix}^T, C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \tag{17}$$

For the observer system (15), the gain of the observer, is defined as $K = P^{-1}C^T R^{-1}$ where P is definite positive solution of the *Riccati equation* described in (18)(Ghanes et al., 2010).

$$\frac{dP}{dt} = -A^T P - PA - PQP + C^T R^{-1} C \tag{18}$$

where the matrices R and Q are symmetric definite positive matrices that are weighting matrices to tune. They can be defined as $Q = diag(q_i, q_i, q_g, q_g)$ and $R = diag(r, r)$, respectively .

3.3 Stability Analysis

In order to prove the stability of the observer proposed in (15)-(17), the practical stability (V. Lakshmikantham and Martynyuk, 1990) is employed in this part. The observer stability is analyzed under parameter uncertainties linked to the deviation of stator resistance due to the temperature variation. Therefore, the system (10)-(**??**) is rewritten in the following form:

$$\begin{cases} \dot{\hat{x}} = A(\omega_e)\hat{x} + v(\omega_e, v_{dq}) + \Delta A x \\ \hat{y} = C\hat{x} \end{cases} \tag{19}$$

where ΔA is uncertain terms of the matrix $A(\omega_e)$ depending only on the stator resistance variation. It is given by:

$$\Delta A = \begin{pmatrix} -\frac{\Delta R_s}{L_{d0}} & 0 & 0 & 0 \\ -0 & -\frac{\Delta R_s}{L_{q0}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{20}$$

with $\|\Delta A\| \leq \rho$, where $\leq \rho$ is a positive constant. Let us now define the estimation error as:

$$e = x - \hat{x}. \tag{21}$$

The dynamic of the estimation error can be expressed as:

$$\dot{e} = (A - KC)e + \Delta A x. \tag{22}$$

Lemma 1. There is $t_0 \geq 0$ and real members $\eta_p^{max} > 0, \eta_p^{min} > 0$, such that $\eta_p^{min}\|e\|^2 \leq V(t,e) \leq \eta_p^{max}\|e\|^2$.

Then, the following theorem about the observer convergence can be rewritten.

Theorem 2. Consider the nonzero input ω_e for the system matrix $A(\omega_e)$ in (16) such that the local observability is fulfilled with respect to (14). Then, the system (15) is an adaptive observer for the machine model (10) with strongly practical stability of the estimation error dynamics (22).

Proof. in order to prove the stability of the estimation error, let us define the following Lyapunov function candidate:

$$V = e^T P e. \tag{23}$$

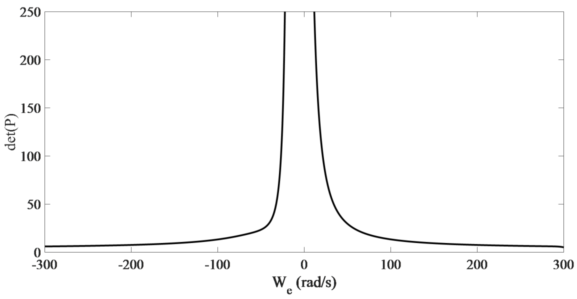

Fig. 1. Determinant of matrix P in a function of ω_e

Taking the time derivative for the function V and replacing (18, 21, 22) to the derivative, it is obtained:

$$\dot{V} = -e^T PQP - e^T CR^{-1}C^T e + \Delta AxPe + e^T P\Delta Ax. \quad (24)$$

According to *Lemma*1 and the physical operation domain of the IPMSM, there is positive l_1 and l_2 such that the following inequalities hold:

$$\|P\| \leq l_1, \|x\| \leq l_2. \quad (25)$$

Substituting (25) into (24), the time derivative of V satisfies the condition.

$$\dot{V} \leq -e^T PQPe - e^T CR^{-1}C^T e + l_1 l_2 \rho e + e^T l_1 l_2 \rho. \quad (26)$$

By taking into account $\mu = l_1 l_2 \rho$ and since $V > e^T PQPe + e^T CR^{-1}C^T e$, (26) can be rewritten as:

$$\dot{V} \leq -e^T PQPe - e^T CR^{-1}C^T e + \widetilde{\mu}\sqrt{V} \quad (27)$$

where

$$\widetilde{\mu} = \frac{\mu}{\sqrt{\eta_p^{min}}}. \quad (28)$$

By using the same procedure such as the strongly practical stability proof (V. Lakshmikantham and Martynyuk, 1990), the strongly practical stability of the proposed observer is proved.

Remark 1. As the gain of the observer K is proportional to P^{-1}, it is interesting to see the determinant of the matrix P for a range of rotor speed. For the proposed system, a numerically calculation of the determinant by numerically solving of (18) is illustrated in Fig. 1 for an ω_e range from -314 rad/s to 314 rad/s.

It can be seen from the curve in Fig. 1 that the determinant of matrix P goes to infinity for the very low and null speeds which means that the gain of the observer K is null on that time. In the other word, for null speeds, the term $K(y-Cx)$ in (15) goes to zero and the observer will be the copy of the system. Thus the observer gain cannot effect on the stability of the system and the estimated variables g_d and g_q are obtained as:

$$\begin{cases} \dot{\hat{g}}_d = 0 \rightarrow \hat{g}_d = \hat{g}_d(t0) \\ \dot{\hat{g}}_q = 0 \rightarrow \hat{g}_q = \hat{g}_q(t0) \end{cases} \quad (29)$$

where t_0 is the initial time for a discrete-time integrator with sampling time T_s and in an interval $[t_0, t_0 + T_s]$. From (29), it can be remarked that if the observer is already converged before standing in null speed, it keeps the estimated variables g_{dq}. For sure, any new magnetic uncertainties in these moments creates a difference between estimated and real variables because of the observability problem in null speed. Nevertheless, there are no explosions for the estimated variables during zero speed as proven in following.

Lemma 3. In the observer (15) and for $\omega_e = 0$, the dynamic of error for i_{dq} state variables and for g_{dq} state variables are practically and Lyapunov stable, respectively.

Proof. for $\omega_e = 0$, (22) becomes as:

$$\begin{cases} \dot{e}_{(1,2)} = A_0 e_{(1,2)} + \Delta A_0 x_{(1,2)} \\ \dot{e}_{(3,4)} = 0 \end{cases} \quad (30)$$

with: $A_0 = \begin{pmatrix} -\frac{R_s}{L_{d0}} & 0 \\ 0 & -\frac{R_s}{L_{q0}} \end{pmatrix}$, $\Delta A_0 = \begin{pmatrix} -\frac{\Delta R_s}{L_{d0}} & 0 \\ 0 & -\frac{\Delta R_s}{L_{q0}} \end{pmatrix}$
then, a new Lyapunov candidate function is defined for $\omega_e = 0$, as following:

$$V_0 = e^T e. \quad (31)$$

By taking the time derivative of 31, it is obtained:

$$\dot{V}_0 = \dot{e}^T e + e^T \dot{e} = \begin{cases} 2e_{(1,2)}^T A_0 e_{(1,2)} + 2e_{(1,2)}^T \Delta A_0 x_{(1,2)} \\ 0 \end{cases}. \quad (32)$$

In (32), as the term $2e_{(1,2)}^T A_0 e_{(1,2)} < 0$, then $\dot{V}_0 \leq 2e_{(1,2)}^T \Delta A_0 x_{(1,2)}$ which proves the practical stability of i_{dq} estimation error dynamics. Furthermore, the estimation error dynamics of g_{dq} are Lyapunov stable as their corresponding derivative Lyapunov functions are equal to zero.

It should be remarked that the matrix Q in the observer system has to be tuned in such a way to have zero gains for the observer at very low speeds.

4. RESULTS

Table 1. IPMSM parameters

Symbol	Quantity	Values
L_{d0}	d-axis linear inductance	3.5 mH
L_{q0}	q-axis linear inductance	5 mH
ϕ_f	permanent magnet flux	0.144 Wb
p	number of pair poles	3
T_l	nominal torque	9 Nm
R_s	stator resistance	0.5 Ω

4.1 Simulation Results

An IPMSM based on the parameters shown in table 1 is simulated in Matlab/Simulink® environment. The magnetic saturation functions (f_{sat-dq}) are considered for the model based on (2). The observer is also simulated in the same environment with sampling time 10^{-4} regarding (15)-(17). The value of L_{d0} in the observer model is considered 3 times bigger than that of the machine model while the magnetic saturation functions are only considered for the simulated machine. The simulation results are illustrated in Figs. 2-3. By using the observed variables g_{dq} on the modified flux estimators (8)-(9), the correct fluxes and consequently the correct torque is obtained as shown in Fig. 2 where Fig. 2(a) and Fig.2(b) describe the real and estimated values for the total flux and electromagnetic torque, respectively. It can be seen from the figures that the estimated variables and the real ones are the same even with unknown magnetic saturation functions and wrong determination of linear inductances. In order to

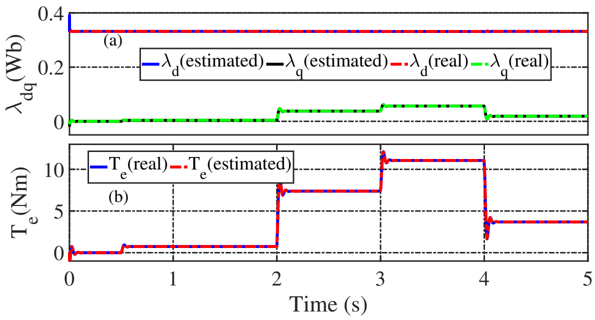

Fig. 2. Simulation results: (a) real and estimated flux linkages, (b) real and estimated electromagnetic torque

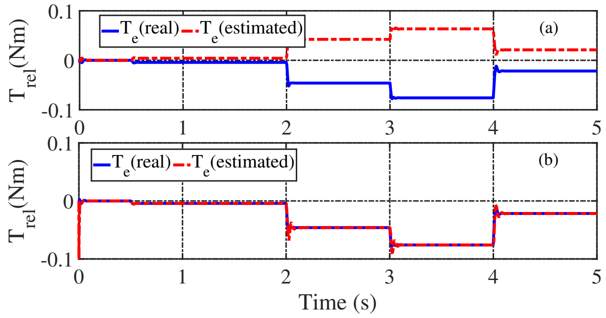

Fig. 3. Simulation results: (a) real and estimated reluctance torque without considering the observed terms g_{dq}, (b) real and estimated reluctance torque with considering the observed terms g_{dq}

show the effect of the magnetic saturation uncertainties of the motor, the reluctance torque of the machine is shown in Fig. 3, without (Fig. 3(a)) and with (Fig. 3(b)) the observed correction terms g_{dq}. It should be noted that it is assumed that the permanent magnet flux is constant or estimated by an observer. Thus, the differences between the real torque and the estimated one is concerned with the reluctance torque. The estimated reluctance torque is not the same as the real one if the terms g_{dq} are not applied to the model (Fig. 3(a)) while they are the same with the proposed observed terms (Fig. 3(b)).

4.2 Experimental Results

An experimental setup composed of an IPMSM rated at 3 kW supplied by a three-phase voltage source inverter is arranged for the experimental tests. A photograph of the test bench is shown in Fig. 4. A similar experimental test as simulation one is considered. The measured currents and torque are considered to be compared with those of estimated since there are no possibility of measuring the real magnetic saturation functions and fluxes. Obviously, there are no saturation functions f_{sat-dq} on the machine model considered in the observer while it is expected to have them in real machine. Fig. 5 shows the measured and estimated currents (Fig. 5(a)) and torque (Fig. 5(b)) where their estimations are converged to the measured ones. It should be noted that the permanent magnet is precisely calculated and does not change during the test to do not effect on the estimation process. Thus, any deviation between the measured torque and the real one is concerned

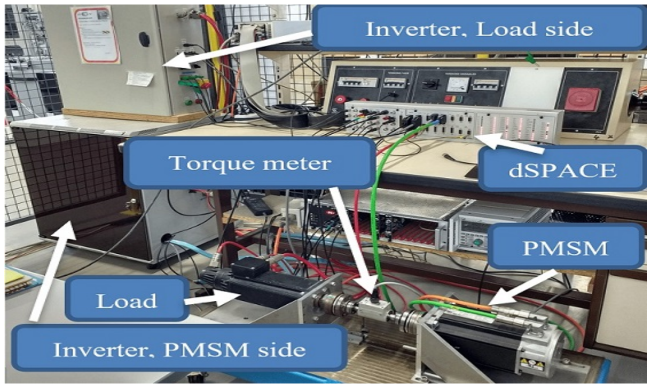

Fig. 4. Test bench

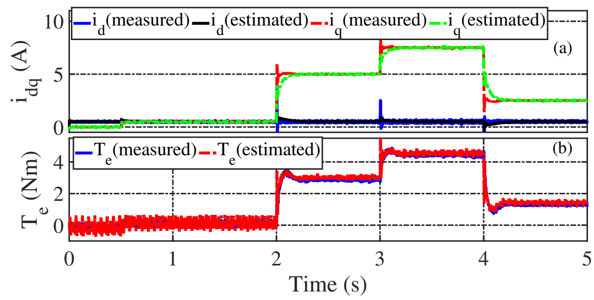

Fig. 5. Experimental results: (a) measured and estimated currents, (b) measured and estimated electromagnetic torque with considering the observed terms g_{dq}

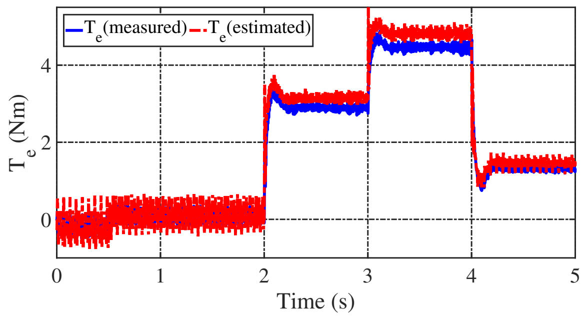

Fig. 6. Experimental results: measured and estimated electromagnetic torque without considering the observed terms g_{dq}

with the inductance changes due to the magnetic saturation.One more time the test is repeated by considering the terms g_{dq} equal to zero for (8)-(9). In this condition, it is assumed that the nominal inductances are precisely calculated and the classical current-flux model (without g_{dq} terms) is used for the flux estimation. The torque results are shown in Fig. 6. It can be seen that there is a difference between the measured torque and the estimated one especially for higher currents despite the precisely determination of linear inductances. By comparing the results shown in Fig. 5(b) and Fig. 6, it is concluded that the observer is well estimating the terms g_{dq} which are concerned with the wrong calculation of linear inductance and/or the magnetic saturation functions. These terms can be considered in (8)-(9) to correct the errors due to magnetic uncertainties in flux and torque estimators.

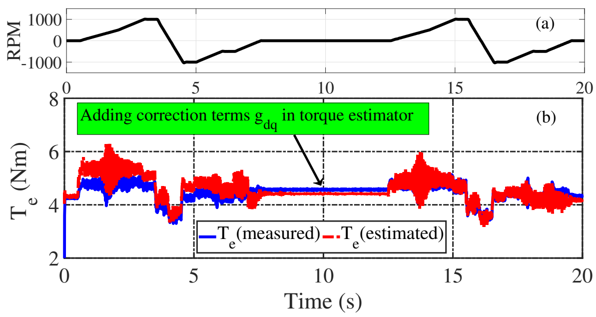

Fig. 7. Experimental results: (a) speed profile, (b) measured and estimated electromagnetic torque

In order to see the stability of the observer at zero speed crossing or at zero speed standing, a variable speed experimental test is prepared. A variable speed profile shown in Fig. 7(a) is considered for the motor during the observation process. The results for estimated torque are shown in Fig. 7(b) where they are compared with the measured ones. From 0 s to 10 s, the terms g_{dq} are observing but are not considering for the flux and torque estimators (3),(8)-(9). As expected, a gap is observed between the measured and estimated torque for the interval. At time 10 s, the the observed terms are added to the estimators while the speed profile is repeated. It can be seen that the gap is disappeared because of the correction terms g_{dq}. It means that the proposed observer is well estimating the fluxes even in variable speed conditions. In point of view of stability, it should be remarked that there are no explosion for the estimated fluxes and consequently the estimated torque at zero speed crossing and even during zero speed standing. As theoretically proved, the observer goes to be the copy of the system for zero speeds. It is also remarked that if the observer has already captured the correct values of g_{dq} corresponding the magnetic uncertainties, they are kept as the system during zero speed standing or at zero speed crossing. As illustrated in Fig. 7(b), the correction terms g_{dq} are added at time 10 s but there are no changes for the estimated torque because of the null speed condition. It means that there are no dynamic for the terms g_{dq} at zero speed as proved in *Remark*1. At the second interval (10 to 20 s) and by the same reason, the terms g_{dq}, that have already collected the uncertainties, are kept during zero crossing at time 16 s. Thus, the estimated torque is the same as the measured one even during the zero speed crossing without any explosion on that time.

5. CONCLUSION

A flux/torque estimator considering the magnetic saturation uncertainties is proposed based on a modified current-flux model of an IPMSM applied in EHV systems. It is proposed to consider two new terms on the model of an IPMSM which defines the influence of wrong determination of linear inductances and the variation of magnetic saturation on flux estimation. An adaptive extended Kalman like observer is designed to observe those terms to be used in flux/torque estimator. It is shown that the gain of the observer regarding the proposed model goes to zero at zero speed which cannot effect on the stability of the system at zero speed crossing as well as zero speed standing. Furthermore, as the uncertainties are considered in the proposed model, they are well observed at zero speed if the observer has already kept them and also if there are no new uncertainties during zero speed operation. The simulation and experimental results are proved the effectiveness of the proposed method.

REFERENCES

Feng, G., Lai, C., Mukherjee, K., and Kar, N.C. (2017). Online pmsm magnet flux-linkage estimation for rotor magnet condition monitoring using measured speed harmonics. *IEEE Transactions on Industry Applications*, 53(3), 2786–2794. doi:10.1109/TIA.2017.2664724.

Ghanes, M., Barbot, J.B., Leon, J.D., and Glumineau, A. (2010). A robust sensorless output feedback controller of the induction motor drives: new design and experimental validation. *International Journal of Control*, 83(3), 484–497. doi:10.1080/00207170903193474.

Hamida, M.A., De Leon, J., Glumineau, A., and Boisliveau, R. (2013). An adaptive interconnected observer for sensorless control of pm synchronous motors with online parameter identification. *IEEE Transactions on Industrial Electronics*, 60(2), 739–748. doi:10.1109/TIE.2012.2206355.

Hermann, R. and Krener, A. (1977). Nonlinear controllability and observability. *IEEE Transactions on Automatic Control*, 22(5), 728–740. doi:10.1109/TAC.1977.1101601.

Holtz, J. (2002). Sensorless control of induction motor drives. *Proceedings of the IEEE*, 90(8), 1359–1394. doi:10.1109/JPROC.2002.800726.

Holtz, J. and Juntao Quan (2003). Drift- and parameter-compensated flux estimator for persistent zero-stator-frequency operation of sensorless-controlled induction motors. *IEEE Transactions on Industry Applications*, 39(4), 1052–1060. doi:10.1109/TIA.2003.813726.

Koteich, M. (2016). Flux estimation algorithms for electric drives: A comparative study. In *2016 3rd International Conference on Renewable Energies for Developing Countries (REDEC)*, 1–6.

Martinez, M., Reigosa, D., Fernández, D., Guerrero, J.M., and Briz, F. (2018). Pmsms torque estimation using pulsating hf current injection. In *2018 IEEE 9th International Symposium on Sensorless Control for Electrical Drives (SLED)*, 96–101. doi:10.1109/SLED.2018.8486060.

Tinazzi, F. and Zigliotto, M. (2015). Torque estimation in high-efficency ipm synchronous motor drives. *IEEE Transactions on Energy Conversion*, 30(3), 983–990. doi:10.1109/TEC.2015.2408214.

V. Lakshmikantham , S.L. and Martynyuk, A. (1990). *Practical Stability of Nonlinear Systems*. World Scientific. doi:https://doi.org/10.1142/1192.

Wang, Q., Zhang, G., Wang, G., Li, C., and Xu, D. (2019). Offline parameter self-learning method for general-purpose pmsm drives with estimation error compensation. *IEEE Transactions on Power Electronics*, 34(11), 11103–11115. doi:10.1109/TPEL.2019.2900559.

Xiao, X., Chen, C., and Zhang, M. (2010). Dynamic permanent magnet flux estimation of permanent magnet synchronous machines. *IEEE Transactions on Applied Superconductivity*, 20(3), 1085–1088. doi:10.1109/TASC.2010.2041435.