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Online PMSM parameters estimation for 32000rpm

Flah Aymen[#1], Martin Novak[*2], Lassaad Sbita[3], Jaroslav Novak[4]

[#]National school of engineering of Gabes,
, Rue Omar ebn el Khattab, Zrig, 6029, Gabes, Tunisia
[1]flahaymening@yahoo.fr
[*]Faculty of mechanical engineering Czech
Czech Technical University in Prague, Praha6, 16607, Czech Republic
[2]Martin.Novak@fs.cvut.cz

Abstract— **A software method, based on a model reference adaptive system (MRAS) is used in this work to online estimate three main Permanent Magnet Synchronous Motor (PMSM) parameters, as stator inductance, resistance and the magnet flux . The proposed estimator is implemented online in the vector control strategy and four input signals as stator currents and voltages are used. The estimation results of the proposed method are based on a real prototype and under a high speed mode, where we touch the 600Hz. Compared to a hardware method, where, some specifics measurements materials are used, the proposed software method prove it efficiency in the obtained results and at the high speed range.**

Keywords-PMSM, MRAS, Simulation, Experimental verification

I. INTRODUCTION

Recently Permanent Magnet Synchronous motor drives have been widely used in many industrial applications and as high performance servo drives, for theirs high efficiency, small size and good controllability [1].Many of the recent applications are based on these motor types. However problems still exist, especially in the control phase. The speed or torque PMSM control can be assured generally by two different control algorithms, the vector or the direct torque control [2]. Each one of these methods is characterised by specific advantages and disadvantages.

Many applications prove the importance and the simplicity of vector control. Therefore, most of the present work is based on this. However, as shown in papers where this method is used, the global performance can downgrade, if motor parameters are changed [3-5].

Generally, the PMSM parameters variation can be a result of external effects, as high temperature, vibration or dist. effectively. The temperature can increase the stator inductance value and decrease the flux produced by the magnet inserted in the rotor [6]. This variation will influence controller parameters used in the vector control method, as the speed and currents controllers. Therefore, an online identification for these motor parameters is extremely required, to assure the best performance.

Many methods are used in the literature in order to assure this operation point. Some applications are based on a real methods using a hardware materiel as presented in [7], where the Tesla meters is used, or in [8-9] where the ohm’s method is applied. These methods, give impressive results, but the online implementation increases the system complexity and value. Therefore, the hardware method is presented as the way that can resolve this problem and assure the desired performance.

The purpose of the herein presented method is to show the efficiency of the MRAS method in PMSM parameters estimation on a real prototype.

The identification software is build based on the MRAS theory, for an online identification of the three main PMSM parameters.

In order to verify the efficiency of the presented algorithm, two hardware methods are used and the obtained results are compared with the obtained one from the software identification algorithm, MRAS.

The organisation of this paper is as follow. After an introduction section, the first part is designed for the PMSM modelling phase, where the hardware methods are presented and the motor equations are elaborated. In section three, the software algorithm is designed and corresponding mathematical equations are implemented. The global scheme is also presented in this part. The real prototype is described in section four and the obtained results are presented in section five. Finally, a conclusion section concludes this work.

II. PMSM MODELLING

In this part we present the results of the PMSM modeling phase using special measurement equipments. ALCRG Meter Tesla BM591 is used to identify the stator resistance and inductance. The obtained results are validated by a second way using the Ohm's method with a Diametral Q130R50D power supply, 2x Pro's kit digital multi-meter MT1232, where the stator resistance value is detected. For the stator inductance, the second method is based on an oscilloscope GDS-806C with probe GTP-060A.From the time constant of a transient characteristic the corresponding value of inductance is acquired. More explanation for these methods is in our previous work in [7].

The obtained PMSM parameters are shown in table I.

During the here presented experiments, the PMSM was controlled with a DSP based controller system. The system assured PMSM operations and feedback control. It was set to fulfill the following conditions:

- The motor was powered with a given current I_q = 9 A until field weakening started
- The start time was 0.4 s and the reached speed was 572 Hz (34 340 min^{-1}).
- The startup current 9 A corresponds to torque 0.98 Nm.

TABLE I
PSMS MODEL PARAMETERS

Model parameter	***Value and units***
R_s	210 [mΩ]
$L_d = L_q$	1100 [μH]
$\cdot_{m}$	0.072 [Wb]

In this work, the main idea is the validations of the obtained PMSM parameters identification results by a software identification method, based on the Model Reference Adaptive System. Therefore, the PMSM mathematical equations must be fixed to start building the software algorithm.

The whole system is modeled with the electrical equations (1), the electromagnetic torque described by (2) and the mechanical equation (3) [6] and [10]. Rs, Ls are respectively the stator resistance and inductance. λ_m is the permanent magnet flux produced by the magnet inserted in the rotor. P is the Poles number, J is the rotor inertia and T_l is the load torque.

$$\begin{cases} v_d = R_s\, i_d + L_s \dfrac{di_d}{dt} - \mu L_s i_q \\ v_q = R_s\, i_q + L_s \dfrac{di_q}{dt} + \mu L_s i_d + \mu\, ^{\text{a}}{}_m \end{cases} \tag{1}$$

$$\begin{cases} T_e = \left(\dfrac{3}{2}\right)\left(\dfrac{P}{2}\right)\left(^{\text{a}}{}_d i_q - {}^{\text{a}}{}_q i_d\right) \\ ^{\text{a}}{}_d = L_s i_d + {}^{\text{a}}{}_m \ \textit{and} \ {}^{\text{a}}{}_q = L_s i_q \end{cases} \tag{2}$$

$$\left(T_e - T_l\right) = \left(\frac{P}{2}\right)\left(J\frac{d\mu}{dt} + f\mu\right) \tag{3}$$

III. THE IDENTIFICATION ALGORITHM

As indicated previously, the MRAS technique is used in this application to implement the identification software algorithm. The stability problem for this type of models is resolved by POPOV theory; more explanation for this point is indicated in our work [6]. This software algorithm simplicity is characterized by the reduced input signals number that will be used to estimate the three main PMSM parameters as the stator resistance, inductance and the rotor flux linkage simultaneously. Effectively, this estimator needs only the online measurement of currents, voltages, and rotor speed to assure the operation.

This software algorithm is characterized by an adjustable model placed in parallel with the real PMSM, wherethe real and the estimated stator currents are compared for generating the current error. An adaptation mechanism is then implemented, using the last current error factors and the real measured speed, for generating the three PMSM parameters. Figure (1), shows the overall software algorithm.

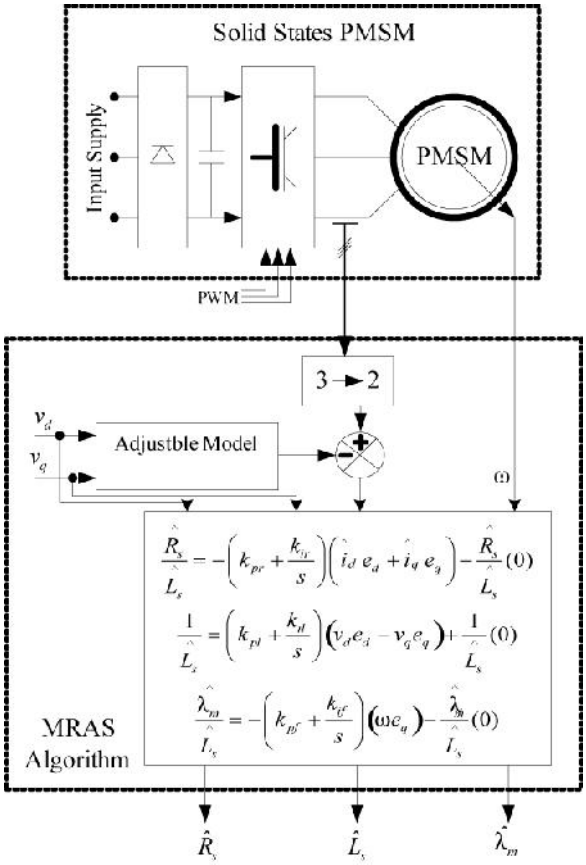

Fig.**1** – Identification scheme

Mathematical implementation

Based on the stator current component expressed in(1), the motor state system can be expressed by equation (4).

$$\dot{X} = AX + BU + C \tag{4}$$

And the corresponding adjustable model can be expressed by equation (5).

$$\dot{\hat{X}} = \hat{A}\hat{X} + \hat{B}U + \hat{C} + G(\hat{X} - X) \tag{5}$$

Where,

- $A = \begin{bmatrix} -^{2} & \mu \\ -\mu & -^{2} \end{bmatrix}$ and $\hat{A} = \begin{bmatrix} -\hat{^{2}} & \mu \\ -\mu & -\hat{^{2}} \end{bmatrix}$

- $B=\begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix}$ and $\hat{B}=\begin{bmatrix} \hat{c} & 0 \\ 0 & \hat{c} \end{bmatrix}$
- $C=\begin{bmatrix} 0 \\ -e_f \end{bmatrix}$ and $\hat{C}=\begin{bmatrix} 0 \\ \mu \hat{I}_f \end{bmatrix}$
- $G=\begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}$

We define $c=\frac{1}{L_s}, \frac{1}{2}=\frac{L_s}{R_s}, e_f=\mu I_f, I_f=\frac{\text{a}_m}{L_s}$.

In the adjustable model, the gain matrix G is chosen to achieve the pre-specified error characteristics, where k1, k2 are two limited positive real constants, manually fixed.

In equation (6), the subtracting result between equations (5) and (4) is expressed.

$$\dot{e}=\Delta A\, e+\Delta B\, U+\Delta C+G\, e \tag{6}$$

As defined in the MRAS theory [10], a feed forward linear model and a non linear feedback system must be created for the adaptation mechanism. Therefore, using the error expression in (6), the obtained linear and non linear model can be created. The result is shown in table II.

TABLE II
LINEAR AND NON LINEAR SYSTEM IN THE MRAS ALGORITHM

Feed forward Linear model	Non linear feedback system
$(A+G)e$	$w=\left\lvert -\Delta A\, X-\Delta B\, U-\Delta C \right\rvert$

According the previous work [6], the MRAS stability problem can be resolved based on POPOV stability theory. The first condition is that the transfer function matrix of the linear forward block must be real and strictly positive.

The second condition is important to the nonlinear feedback block. Effectively,the integral inequality of the non linear feedback systemmust assure this inequality.

$\int_0^{t1} w^T e\,dt \geq -\text{¥}^2$ where γ2 is a positive constant at any time t.

Therefore, started from those conditions, and based on the adaptive laws of parameter designed as a PI style as demonstrated in equations (7), the parameters expressions can be presented in (8).

$$\begin{cases} \Delta A=\int_0^t (e^T\, \hat{X}.f_{ir}.+e^T\, \hat{X}.f_{pr})dt \\ \Delta B=\int_0^t (e^T.U.f_{il}.+e^T.U.f_{pl})dt \\ \Delta C=\int_0^t (e^T.f_{ic}.+e^T.f_{pc})dt \end{cases} \tag{7}$$

$$\begin{cases} \frac{\hat{R}_s}{\hat{L}_s}=-\left(k_{pr}+\frac{k_{ir}}{s}\right)\left(\hat{i}_d\, e_d+\hat{i}_q\, e_q\right)+\frac{\hat{R}_s}{\hat{L}_s}(0) \\ \frac{1}{\hat{L}_s}=\left(k_{pl}+\frac{k_{il}}{s}\right)\left(v_d e_d+v_q e_q\right)+\frac{1}{\hat{L}_s}(0) \\ \frac{\hat{\text{a}}_m}{\hat{L}_s}=-\left(k_{pf}+\frac{k_{if}}{s}\right)\left(\mu e_q\right)+\frac{\hat{\text{a}}_m}{\hat{L}_s}(0) \end{cases} \tag{8}$$

IV. DESCRIPTION OF THE EXPERIMENTAL SYSTEM

The experimental setup is shown in Fig. 2. The PMSM is connected to an turbocharger. Between the PMSM and the turbocharger there is a torque sensor. During the experiments the machine was powered with a rectifier from the power supply network. The rectified voltage supplies an insulated gate bipolar transistor (IGBT) inverter. The inverter uses a power module SKM75GD124D and IGBT/MOSFET driver SKHI61 both from Semikron. The whole system is being prepared to work as a micro-turbine generator; the turbine is created by means of a standard car turbocharger. At the present time, the machine is used as a motor i.e. providing mechanical energy to the turbocharger. When a suitable source of pressure air or exhaust gas will be available, it will be run in generator mode to produce electrical energy. The PMSM parameters are summarized in table III.

TABLE II~~II~~II
PMSM PARAMETERS

Motor type: 2AML406B-090-10-170	Manufacturer: VUES Brno, CZ
V_{dc} = 560 V	n_n = 25 000 min-1 , n_{max} = 42 000 min-1
I_{n_rms} = 11 A	K_E = 7,3 V/ kRPM
T_n = 1,2 Nm	

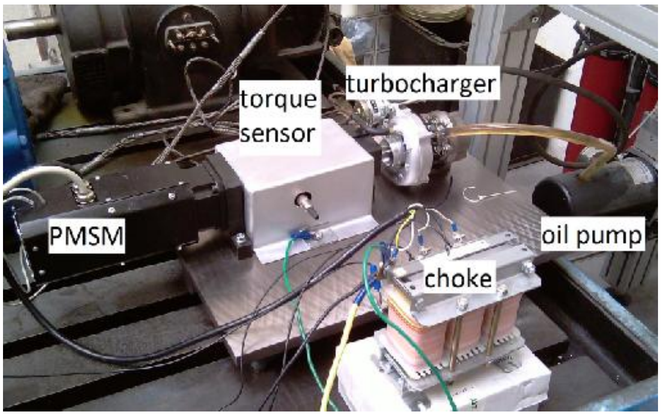

Fig.2 - Experimental setup

V. RESULTS DISCUSSION

In this part, the results of the proposed estimation method are presented. As indicated previously, the vector control scheme is elaborated in order to control the motor speed. The three specific PI controllers are implemented to control the currents and the speed.

In this application, the high speed mode is required; therefore, the field weakening bloc is also implemented to generate the reference direct stator current. After fixing the PI parameters, the MRAS estimator is implemented, using the stator voltages and currents, to online estimate the PMSM parameters.

In this application, the high speed mode is tested. The nominal motor speed is equal to 25000 rpm and the desired speed is 36000 rpm, which corresponds to an angular speed of 600 Hz in the chart. The requested I_d current was set to 0 A. Current I_q was set to 1.5 A in the experiment, to achieve the required speed profile. Figure (3) to (5) show the corresponding currents and speed results.

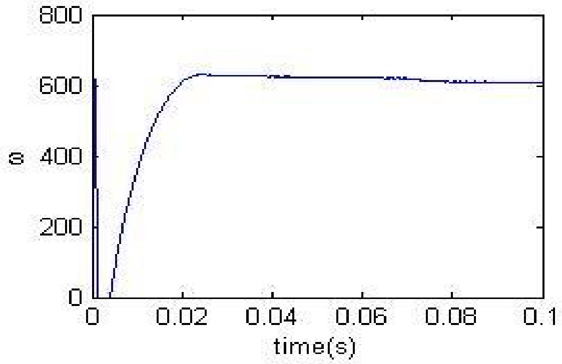

Fig. 3 : Speed results

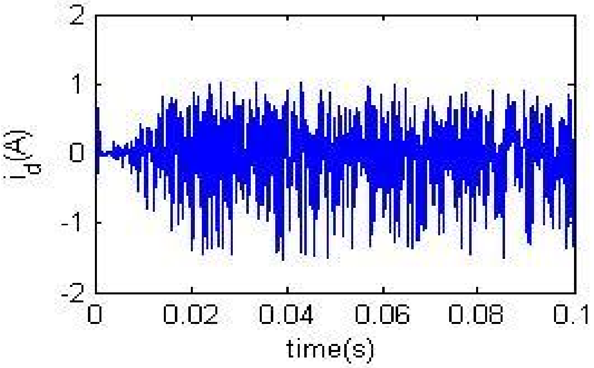

Fig. 4: Direct stator current comportment

In these conditions, the obtained PMSM parameters estimations results are as follow:

For the stator estimation case, we can observe in figure (6), that there is relatively large variation from the estimated value of R_s, by the MRAS method. The estimated value for standstill is 210 mΩ.

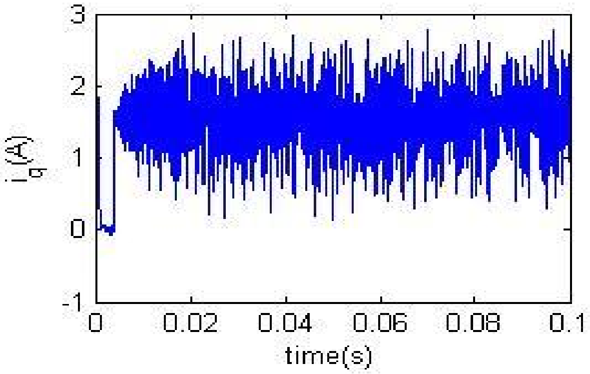

Fig. 5: Quadrature stator current comportment

For the desired speed 36000 rpm, R_s changes to 250 mΩ. The relative change is about 20 %. As the experiment took only a short time, the variations are not expected to be caused by the change of temperature. A clear dependence between angular velocity ω and Rs can be found.

The estimated variations of the permanent magnet magnetic flux are shown in figure (7).The value decreases as proved by the physical theory of the flux weakening mode. However the variation is very small, the accuracy is limited by the accuracy of the experiments and noise.

The behavior of machine inductance L_s is different as shown in figure (8). After the initial undershoot, there is small increase in inductance. The changes between the initial and instantaneous value of L_s are quite small. Due to the limited precision of the measured data and present noise, it is not possible to draw a conclusion about the increase of L_s from this experiment. The initial value of L_s was however been estimated correctly and corresponds to the measured value of inductance.

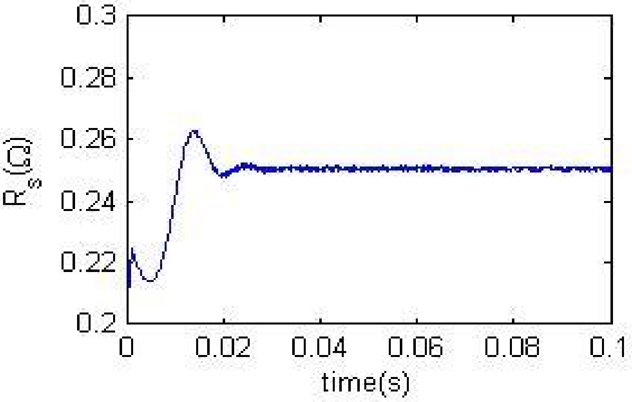

Fig. 6 : Stator resistance estimation

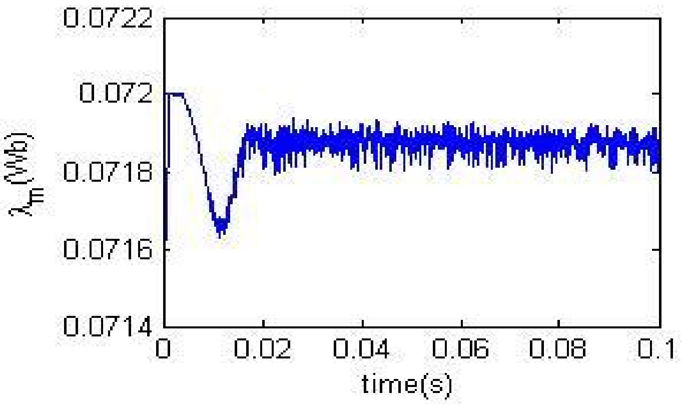

Fig. 7 : Magnet flux estimation

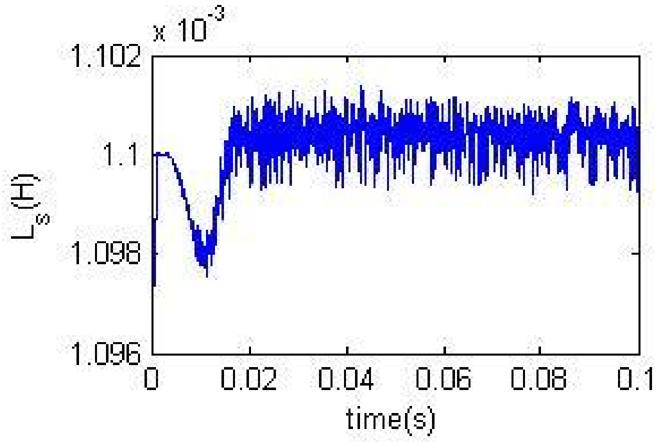

Fig. 8 : Stator inductance estimation

Remark: All time axis must be multiplied by 10000*66e-3 to obtain the real time axis.

VI. CONCLUSION

In this work, a software method, based on the MRAS theory is implemented to estimate online the three main PMSM parameters; stator inductance L_s; resistance R_s and the magnet flux λ_m produced by the rotor. The software estimation method is implemented in the vector control strategy, and tested on a real prototype. The high speed mode is tacked as a condition to prove the efficiency of the proposed software method face to the hardware one. The corresponding mathematical expressions are also given to make easy the implementation of the proposed method. The same algorithm will be adapted to a salient motor in a future works.

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