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High speed PMSM control without speed encoder based on Q-MRAS observer

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1. Nomonclature

PMSM	Permanent magnet synchronous motor
HSA	High speed algorithm
v_d, v_q	Direct and quadrature stator voltages
λ_d, λ_q	Direct and quadrature stator fields
i_d, i_q	Direct and quadrature stator currents
L_d, L_q	Direct and quadrature stator inductances
ω, ω_b	rotor speed and rated Speed
λ_m	Permanent Magnet flux
R_s	Stator resistance
T_l	Load torque
P	Pairs poles number
J	Rotor inertia coefficient

Abstarct
In this paper, the Permanent magnet synchronous motor is operated at the high speed mode basing on the vector control strategy. This running mode is unsured by the High speed algorithm, where its principle deals with a direct stator current reduction strategy. In addition, the aim of this paper it to control the motor without speed encoder. Therefore, the Model Reference Adaptive System (MRAS) is performed to avoide the speed encoder use and to perform an efficient reactive power based one.

2. Introduction

Electric motor uses are in increasing way. Nowadays, Robots use is well spread in manufacturing industry, military field, space exploration, transportation, and medical applications. Therefore, the consideration of performance robustness, rapidity and precision are required for many specified applications [1] and [2].

Many electrical motor types are used in these systems. Zhu in [3] has established a comparative study on these electrical machines and drives. In his approach, the induction machines, switched reluctance machines and the permanent magnet synchronous motors are compared. The obtained results proved that the permanent magnet synchronous motor is more efficient face to the others types.

Based on this motor type, many control researches are established. Several control strategy were proposed and tested for controlling this device, such as vector control or direct torque control strategy as presented in [4], [5].

The speed control target is generally the goal in each type of application. In the conventional control method, the speed feedback is assured by a speed encoder. However, the high cost and complexity architecture, present the disadvantage. Therefore, many software methods are proposed in the literature as Sliding mode speed observer, neural speed observer or other techniques based on MRAS. The versions used MRAS techniques are exposed in many versions. Each one presents advantageous and disadvantageous.

In this work, we long for building a robust PMSM control loop without speed encoder, based on MRAS reactive power. This proposed speed encoder will be tested under high speed region.

As this application needs a high speed running mode, the field weakening operation is implemented, based on Morimoto approaches as presented in [6] and [7].

Consequently, the obtained new control scheme is implemented on the MATLAB/Simulink environment and tested in a wide speed range.

This paper is organized as fellow. After a general introduction section, the second one is designed for describing the control scheme. The MRAS reactive power is described in the third part. Then the simulation results are presented and discussed. Finally the conclusion is presented.

3. Global PMSM control scheme: Description

In this application, the vector control method is used to operate the motor. The high speed mode is required in this application; therefore, the field weakening method is used to assure this running mode [8]. Effectively, its principle is similar to the DC machine, where the flux is a separately controlled entity. So, a flux minimization is important for attained a high speed region. The appeared problem is present by the flux produced by the rotor magnet (λm), which presents a difficulty for minimizing the total motor flux. Generally, the rated speed mode is assured by keeping the direct stator current equal to zero [9]. Based on the flux expressions as presented in (1), the high speed mode can be touched only if the direct flux component is reduced. This operation can be assured only by reducing the direct stator component to the negative region.

$$\begin{cases} \lambda_d = L_d i_d + \lambda_m \\ \lambda_q = L_q i_q \end{cases} \quad (1)$$

The problem can appear in this phase is related to find the necessary theory for generating the required direct stator current, that assure this running mode in a safety conditions. The idea refers to the currents and voltages below a maximum value. The maximum of current and voltage are usually set by the inverter and the limit system of equations, take into account the maximum voltage and maximum current as expressed in (2). The values I_{max} and Vmax are respectively the maximum inverter phase-current and phase-voltage amplitudes.

$$\begin{cases} I_d^2 + I_q^2 \le I_{\max}^2 \\ V_d^2 + V_q^2 \le V_{\max}^2 \end{cases} \quad (2)$$

Based on theses limit equations, the field weakening zone can be exploited. Fig (1) presents two types of circles one for the current limitation and one for the voltage limitation condition. The radius of the voltage limitation is proportional to the speed inverses. Effectively, when the speed increases, the voltage circle radius decreases. And the voltage circle center depends on the PMSM parameters.

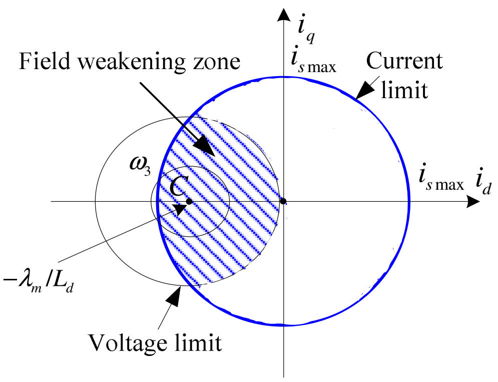

Fig. 1. Field weakening strategy diagram

Based on the PMSM mathematical modeling, as voltage expression in (3), and by considering that the saturation, eddy currents and hysteresis iron losses effects are negligible, the corresponding direct stator current expression can be designed by (4) and the corresponding High Speed Algorithm (HAS) is designed in figure (2) .

$$\begin{cases} v_d = R_s\, i_d + L_d \dfrac{di_d}{dt} - \omega L_q i_q \\ v_q = R_s\, i_q + L_q \dfrac{di_q}{dt} + \omega L_d i_d + \omega \lambda_m \end{cases} \quad (3)$$

$$i_d^* = \frac{\sqrt{V_{\max}^2 - \left(\omega L_q i_q\right)^2} - \omega \lambda_m}{\omega L_d} \quad (4)$$

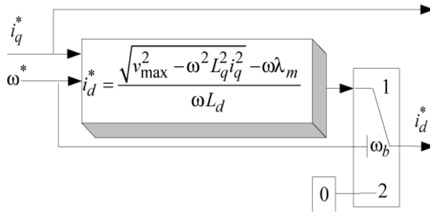

Fig.2. High Speed Algorithm (HAS)

4. MRAS Reactive power Speed Observer

Model reference adaptive system technique can be classified as one of the efficiency estimation methods. Face to the Back-Emf and state observer methods, this one can be classified as the most competent. In some literatures, authors compare this one by the intelligent estimation methods, where neuron and fuzzy solutions can be also attractive. However, the needs of knowing database informations present the disadvantage of these solutions. Therefore, most of the reported works based on methods used mathematical models as MRAS, Lunberger, etc… and the obtained results prove the efficiency of these solution.

The MRAS principle is based on two mathematical models, called "reference and adjustable models" as presented in figure (3). The outputs will be compared and used in a specific algorithm to identify or to estimate a designed parameter. Generally, this output signal will be also used in the adjustable model. The problem can be appeared in the MRAS estimator is related to the stability phenomenon, where the global system can be instable if the adjustable and the adaptation mechanism are not well selected and identified. This problem can be resolved by the Popov's Hyperstability criterion as demonstrated in [10].

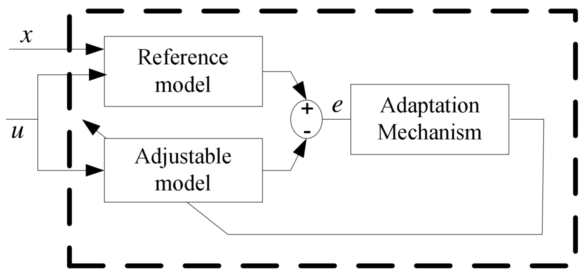

Fig. 3: Basic structure of MRAS

In our application, the speed value will be online estimate, in order to eliminate the real speed encoder. Therefore, we try to elaborate the required mathematical equations and build the necessary Speed observer. It is important to indicate that many versions of MRAS can be used to obtain the goal. Back-EMF (E-MRAS), reactive power (Q-MRAS) [11] and active power (A-MRAS) are these different versions. Each of these methods is characterized by specific advantageous and disadvantageous.

Based on the different works, E-MRAS and A-MRAS [11] are sensitive to the stator resistance variation, however the reactive power version is insensible to this parameters version. Refers to our application, where the high speed mode will be running, the motor stator resistance value can increase by increasing the motor temperature, therefore, Q-MRAS will be used in our application.

The corresponding mathematical expressions are as follow: The reactive power expression is presented in (1)

$$Q_s = v_q i_d - v_d i_q \tag{1}$$

Based on the stator voltage expression, the new reactive power formula can be elaborated as equation (2).

$$Q_s = \omega\left(L_d i_d^2 + L_q i_q^2\right) + \left(L_d i_d \frac{di_q}{dt} - L_q i_q \frac{di_d}{dt}\right) + \omega i_d \lambda_m \tag{2}$$

In the stable region, i_d and i_q can be fixed as a constant components, therefore the new expression of equation (2) become in (3).

$$Q_s = \omega\left(L_d i_d^2 + L_q i_q^2\right) + \omega i_d \lambda_m \tag{3}$$

Started form equation (3), the adjustable model can be illustrated using currents and speed signals as indicated in equation (4).

$$\hat{Q}_s = \hat{\omega}\left(L_d \hat{i}_d^2 + L_q \hat{i}_q^2\right) + \hat{\omega}\hat{i}_d \lambda_m \tag{4}$$

After obtained the reference and the adjustable model, the second phase consists to build the adaptation mechanism.

By subtracting equation (4) from (1), the reactive power error signal can be expressed in equation (5) and the overall Q-MRAS scheme can be illustrated in figure (4).

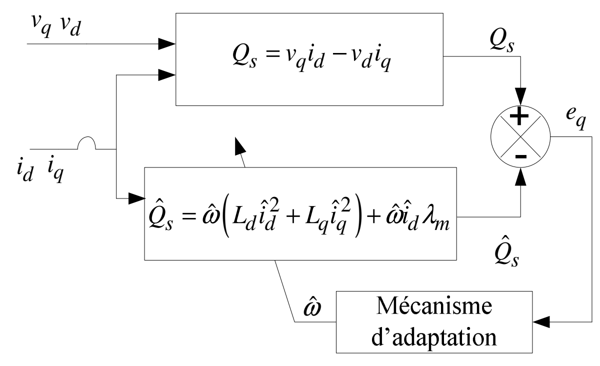

Fig.4 : Q-MRAS Structure

$$\begin{aligned} e_q &= Q_s - \hat{Q}_s \\ &= v_q i_d - v_d i_q - \hat{\omega}\left(L_d \hat{i}_d^2 + L_q \hat{i}_q^2\right) - \hat{\omega}\hat{i}_d \lambda_m \\ &= \alpha + \hat{\omega}\beta \end{aligned} \tag{5}$$

Based on POPOV hyper stability criterion, identify the linear and non linear part in the system is necessary, where the system decompression must be as indicated in figure (5).

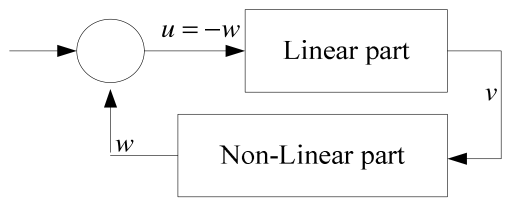

Fig.5 : Linear and non linear decompression

Based on the two POPOV conditions, as the linear model must be strictly positive and the nonlinear model must satisfy the inequality expressed in (6), the adaptation mechanism can be expressed.

$$\int_0^t v^T(w)dt \geq -\gamma_0^2 \tag{6}$$

Starting verifying the first POPOV condition, we can conclude that this one can be guaranteed by using a sign bloc.

The second condition can be assured by the system of equations (7), where $w = -\alpha - \hat{\omega}\beta$.

$$\begin{cases} \int_0^t v^T(-\alpha)dt \geq -\gamma_0^2 \\ \int_0^t v^T(-\hat{\omega}\beta)dt \geq -\gamma_1^2 \end{cases} \tag{7}$$

The first part of the system (7) is guaranteed due to :

$$\alpha \leq 0 \Rightarrow -\alpha \geq 0 \Rightarrow \int_0^t v^T(-\alpha)dt \geq 0$$

The second part is also guaranteed if we applied this condition

$$\begin{cases} v = De_q \quad , D \text{ is the sign bloc} \\ \hat{\omega} = (k_p + \frac{k_i}{s})v \end{cases}$$

The global Q-MRAS structure can be then illustrated in Figure (6).

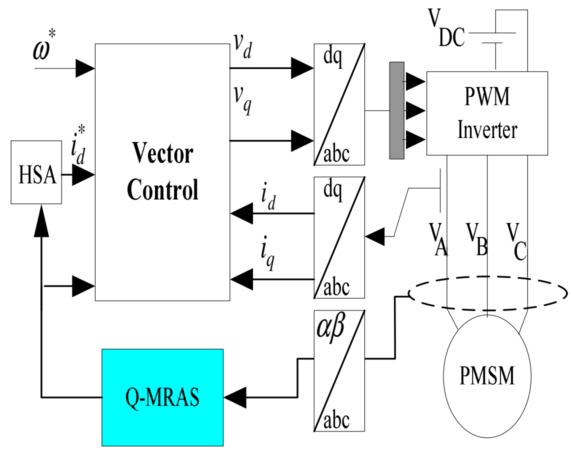

Fig.7 Global control scheme

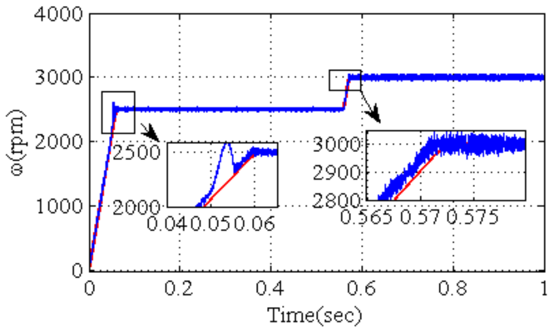

Fig.8 Real and estimate speed results

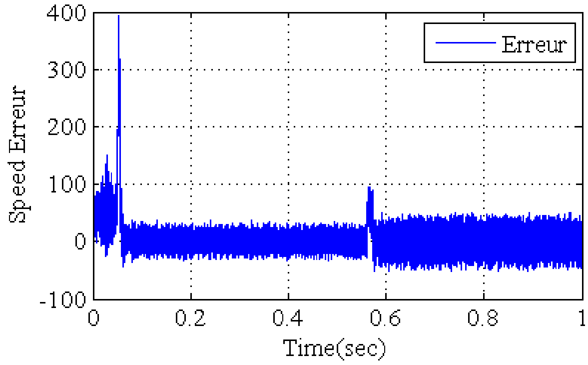

Fig.9 Speed errors

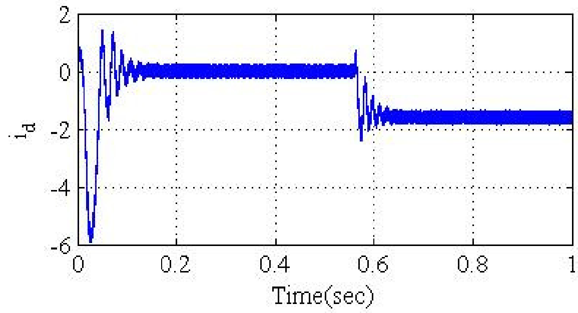

Fig.10 Direct stator current comportment

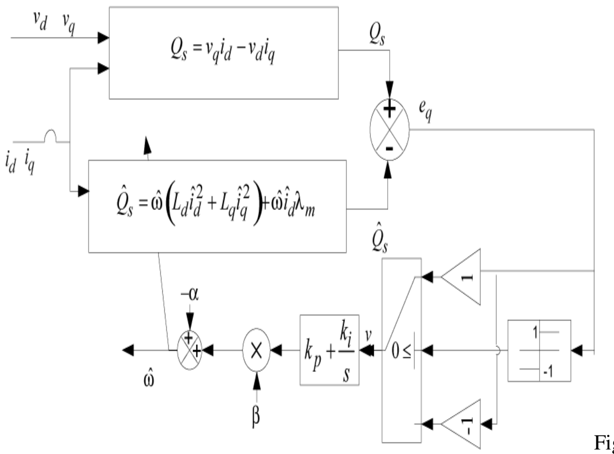

Fig. 6 Q-MRAS Final structure

5. Results Discussion

In this section, the obtained results are illustrated and discussed. The global control scheme applied in this work is presented in Figure (7), where the vector control strategy is used and the High Speed Algorithm is implemented. The Q-MRAS speed observer is also used to assure the control without speed observer.

The given speed form start from 0 rpm to the rated speed 2500rpm, then after 0.5sec, the high speed mode is touched by 3000rpm.

The high speed principle is shown on current figures (10) and (11). In the rated speed the direct stator current is fixed to zero, however in the high speed mode, this component decrease to the negative region. The transversal current decrease also in the high speed mode because the applied load torque is similar to the electric vehicle, where the global weigh of the vehicle drop off in this speed region. That equivalent to diminish of the load torque applied on the motor.

Figure (8), presents the real and the estimate speed, for this configuration cited previously. It is clear that estimate speed follow the real one, which proves the estimator performance, in the rated and the high speed mode. Some perturbation in the initial phase is present due to the PI parameters must be adjusted and a chattering phenomenon is present due to the sign bloc used in the adaptation mechanism. Figure (9), presents the estimation speed error and the good performance is clearly shown.

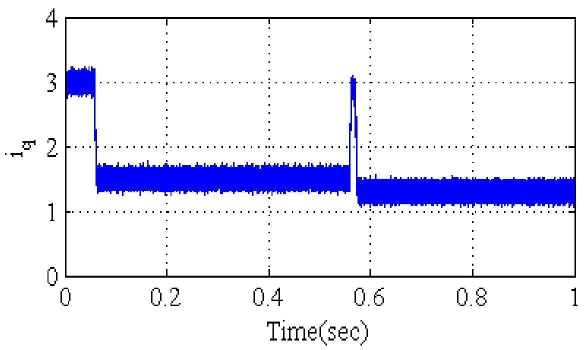

Fig.11 Transversal stator current comportment

6. Conclusion

In this paper, the PMSM control without speed encoder is performed. The Model Reference Adaptive System based on reactive power characteristics is used to assure the speed encoder. The vector control strategy is used to assure the motor control and the High Speed Algorithm is applied for running in this mode. The Q-MRAS good performance is clearly shown on the obtained figures.

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