

Speed Sensorless IFOC of PMSM Based On Adaptive Luenberger Observer

Grouz Faten, Sbita Lassaad

Abstract—In this paper, Speed Sensorless Indirect Field Oriented Control (IFOC) of a Permanent Magnet Synchronous machine (PMSM) is studied. The closed loop scheme of the drive system utilizes fuzzy speed and current controllers. Due to the well known drawbacks of the speed sensor, an algorithm is proposed in this paper to eliminate it. In fact, based on the model of the PMSM, the stator currents and rotor speed are estimated simultaneously using adaptive Luenberger observer for currents and MRAS (Model Reference Adaptive System) observer for rotor speed. To overcome the sensitivity of this algorithm against parameter variation, adaptive for on line stator resistance tuning is proposed. The validity of the proposed method is verified by an extensive simulation work.

Keywords—PMSM, Indirect Field Oriented Control, fuzzy speed and currents controllers, Adaptive Luenberger observer, MRAS.

I. INTRODUCTION

INDUSTRIAL applications need more and more efficient and accurate performances from motor drives. Induction machines are used widely but in recent years; permanent magnet synchronous motors (PMSM) are increasingly applied in several areas such as tractions, automobiles, robotics and aerospace technology because of advantages such as: high power/ weight ratio, large torque, inertia ratio, smooth torque operation, controlled torque at zero speed, high speed operation, high torque production capability, high efficiency, compact structures [1].

However, the need of position or velocity sensors in order to apply effective vector-control algorithms is one of their main constraints [2]. Indeed, there are several disadvantages of those sensors such as higher number of connection between motor and its driver, additional cost, susceptibility to noise and vibrations, extra space, volume and weight on the overall actuator [3].

Therefore, vector-control methods in the absence of any position or speed sensor have been investigated by many researchers [2, 4]. Some techniques were proposed in literature. These techniques are generally based on the state observer or Luenberger observer [5], MRAS method [6], and extended Kalman filters.

Grouz Faten is with the National Engineering School of Gabès, Tunisia (corresponding author to provide phone: 216-75-392-100; fax: 216-75-392-190; e-mail: grouz_faten@yahoo.fr).

Sbita Lassaad is with the National Engineering School of Gabès, Tunisia (corresponding author to provide phone: 216-75-392-100; fax: 216-75-392-190; e-mail: lassaad.sbita@enig.rnu.tn).

In this paper, to overcome problems related to the mechanical speed sensor, the adaptive Luenberger observer for speed and stator resistance estimation has been proposed. This algorithm associated with fuzzy speed and current controllers in a field orientation strategy leads to a performed solution for PMSM high dynamic drives.

II. MATHEMATICAL MODEL OF PMSM AND VECTOR CONTROL

The dq equations in the reference frame of the PMSM are:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} + p w_r \begin{bmatrix} -\lambda_q \\ \lambda_d \end{bmatrix}. \quad (1)$$

The dq axis stator flux linkages are:

$$\begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \Phi_v \\ 0 \end{bmatrix}. \quad (2)$$

The model is nonlinear because it contains product terms such as speed with i_d or i_q .

The dynamic behaviour and electromagnetic torque equations are expressed by:

$$T_{em} - T_L = J \frac{dw_r}{dt} + f w_r \quad (3)$$

$$T_{em} = \frac{3p}{2} (\Phi_v i_q + (L_d - L_q) i_d i_q). \quad (4)$$

The dq model of PMSM has been used to examine the transient behavior of a high performances vector controlled PMSM servo drive. The direct or 'd' axis is aligned with permanent magnet flux linkage phasor Φ_v , so that the quadrature or 'q' axis is orthogonally aligned with the resulting back e.m.f phasor.

If i_d is forced to be zero, then

$$\lambda_d = \Phi_v ; \lambda_q = L_q i_q. \quad (5)$$

For constant flux operation, the electromagnetic torque is :

$$T_{em} = \frac{3p}{2} \Phi_v i_q. \quad (6)$$

The torque equation for PMSM resembles to that of the regular DC motor. Therefore, it may facilitate very efficiently the control of the machine. The motor currents are decomposed into i_d and i_q components in the rotor based dq coordinates system. The maximum torque is obtained with $i_d = 0$ which corresponds to the case when the rotor and stator fluxes are perpendicular. The operation of the drive is then similar to that of armature current controlled DC motor. The drive behavior can be adequately described by a simplified model expressed by equation (6) [7].

III. CONTROL STRUCTURE

Fig.1 illustrates the block diagram of IFOC scheme based PMSM drive considered in this investigation. The drive consists of adaptive Luenberger observer for speed estimation, fuzzy hysteresis current control, and AC machine. The rotor speed w_r is compared with the reference speed w_{ref} . The resulting error is processed in the fuzzy speed controller for each sampling interval. The output of this is considered to be the reference torque T_{em}^* .

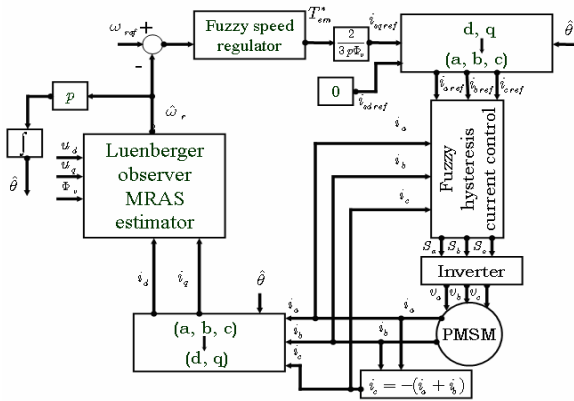


Fig.1 Block diagram of Indirect Field Oriented Control scheme based PMSM drive

IV. FUZZY LOGIC SPEED CONTROLLER

The fuzzy logic control has two inputs and one output U^* . The input variables used are the speed error $e(k)$ and change in speed error $\Delta e(k)$:

$$e(k+1) = w_{ref} - w_r(k+1) \tag{7}$$

$$\Delta e(k+1) = e(k+1) - e(k) \tag{8}$$

To obtain normalized inputs and output for fuzzy logic controller, the constant gain blocks are used as scaling factors G_1, G_2, G_3 :

$$e_N(k+1) = e(k+1) \cdot G_1 \tag{9}$$

$$\Delta e_N(k+1) = \Delta e(k+1) \cdot G_2 \tag{10}$$

$$U^*(k) = U(k-1) + G_3 \cdot \Delta U(k) \tag{11}$$

The fuzzy logic control consists of three stages: the fuzzification, rule execution, and defuzzification. In the first stage, the crisp variables $e(k)$ and $\Delta e(k)$ are converted into fuzzy variables $e^*(k)$ and $\Delta e^*(k)$ using the triangular membership functions shown in Fig.2 and Fig.3. Moreover the triangular membership function of variation in the command ΔU and speed control surface are shown in Fig.4 and Fig.5.

The universe of discourse is divided into the fuzzy sets symbolized as follows: NL (negative large), NM (negative middle), NS (negative small), ZE (zero), PS (positive small), PM (positive middle) and PL (positive large). Each fuzzy variable is a member of the subsets with a degree of membership varying between 0 and 1.

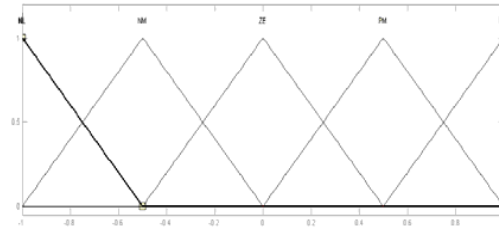


Fig.2 The membership function of e

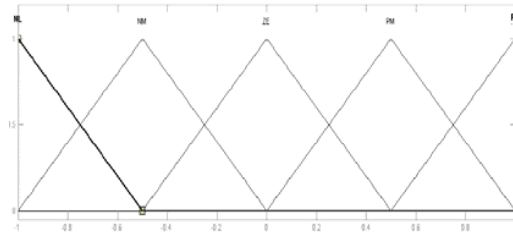


Fig.3 The membership function of Δe

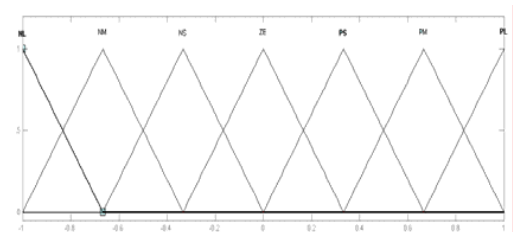


Fig.4 The membership function of ΔU

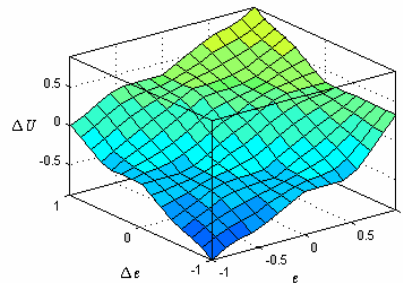


Fig.5 Speed control surface

In the second stage of the fuzzy logic control, the fuzzy variables $e^*(k)$ and $\Delta e^*(k)$ are processed by an inference engine that executes a set of control rules contained in rule bases which is described in table I.

Different inference algorithms can be used to produce the fuzzy set values for the fuzzy variable ΔU . In this paper, the sum-prod inference algorithm is used. The inference engine output variable is converted into a crisp value T_{em}^* in the defuzzification stage.

Various defuzzification algorithms have been proposed in the literature [8]. In this paper, the centroid defuzzification algorithm is applied, in which the crisp value is calculated as the centre of gravity of the membership function.

TABLE I
DESCRIPTION OF THE INFERENCE

| | | | | | |
|-------------------|----|----|----|----|----|
| e Δe | NL | NM | ZE | PM | PL |
| NL | NL | NM | NS | NS | ZE |
| NM | NM | NS | NS | ZE | PS |
| ZE | NS | NS | ZE | PS | PS |
| PM | NS | ZE | PS | PS | PM |
| PL | ZE | PS | PS | PM | PL |

V. FUZZY HYSTERESIS CURRENT CONTROL

To reduce the current harmonics, three fuzzy current controllers are introduced.

In fact, each fuzzy logic controller has two inputs and one output ΔU_j ($j=a, b$ or c). The input variables used are the current error $e_j(k)$ and change in current error $\Delta e_j(k)$:

$$e_j(k) = i_{j\text{ref}} - i_j(k) \tag{12}$$

$$\Delta e_j(k) = e_j(k) - e_j(k-1) \tag{13}$$

With: $j=a, b$ or c .

The universe of discourse is divided into the fuzzy sets symbolized as follows: NL (negative large), NS (negative small), ZE (zero), PS (positive small), PL (positive large), N (negative) and P (positive). Each fuzzy variable is a member of the subsets with a degree of membership varying between 0 and 1.

Moreover the triangular membership function of the error e_j , error variation Δe_j , variation in the command ΔU_j and the current control surface are shown respectively in Fig.6, Fig.7, Fig.8 and Fig.9.

The control strategy depends firstly on the inferences (rules). To simplify their descriptions table II is dressed. The method of inference selected here is known as sum-prod.

In this paper, the centroid defuzzification is adopted.

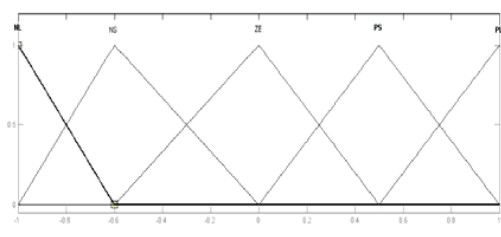


Fig.6 The membership function of e_j

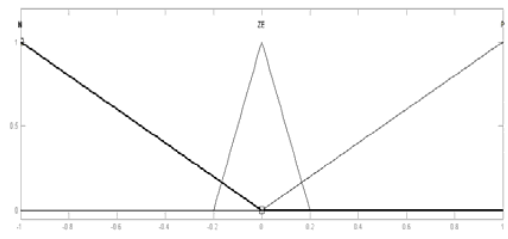


Fig.7 The membership function of Δe_j

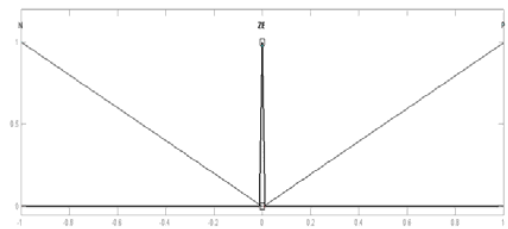


Fig.8 The membership function of ΔU_j

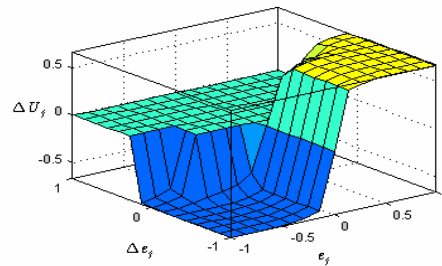


Fig. 9 Current control surface

TABLE II
DESCRIPTION OF THE INFERENCE

| | | | | | |
|-----------------------|----|----|----|----|----|
| e_j Δe_j | NL | N | ZE | PS | PL |
| | | S | | | |
| N | N | N | ZE | P | P |
| ZE | N | ZE | ZE | ZE | P |
| P | ZE | ZE | ZE | ZE | ZE |

The inverter switching conditions are:

$$S_j = 1 \text{ if } \Delta U_j \text{ is positive.}$$

$$S_j = 0 \text{ if } \Delta U_j \text{ is null.}$$

(14)

$$S_j = -1 \text{ if } \Delta U_j \text{ is negative.}$$

With: $j=a, b$ or c .

But, the three level current controlled inverter devices ON/OFF conditions are:

$$S_j = 1 \text{ if upper transistor of inverter is on}$$

$$= -1 \text{ if lower transistor of inverter is on.}$$

$$= 0 \text{ if diode of inverter is on.}$$

with j : a, b and c.

VI. LUENBERGER ADAPTIVE OBSERVER

The simplified state space of PMSM is given by:

$$\begin{cases} \frac{dX}{dt} = AX + BU \\ Y = CX \end{cases} \quad (15)$$

with:

$$X = [\hat{i}_d \quad \hat{i}_q]^T; U = [u_d \quad u_q \quad \Phi_v]^T; Y = [\hat{i}_d \quad \hat{i}_q]^T$$

$$A = \begin{bmatrix} -\frac{R}{L_s} & p\omega_r \\ -p\omega_r & -\frac{R}{L_s} \end{bmatrix}; B = \begin{bmatrix} \frac{1}{L_s} & 0 & 0 \\ 0 & \frac{1}{L_s} & -\frac{p\omega_r}{L_s} \end{bmatrix}; C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The second order Luenberger observer (shown in fig.1) is given by:

$$\begin{cases} \frac{d\hat{X}}{dt} = A_1(\hat{\omega}_r, \hat{R})\hat{X} + B_0U + K(Y - \hat{Y}) \\ \hat{Y} = C\hat{X} \end{cases} \quad (16)$$

With:

$$\hat{X} = [\hat{i}_d \quad \hat{i}_q]^T; Y = [\hat{i}_d \quad \hat{i}_q]^T$$

$$A_1(\hat{\omega}_r, \hat{R}) = \begin{bmatrix} -\frac{\hat{R}}{L_s} & p\hat{\omega}_r \\ -p\hat{\omega}_r & -\frac{\hat{R}}{L_s} \end{bmatrix}; B_0 = \begin{bmatrix} \frac{1}{L_s} & 0 & 0 \\ 0 & \frac{1}{L_s} & -\frac{p\hat{\omega}_r}{L_s} \end{bmatrix}$$

The matrix gain K is chosen so that the poles of $(A_1 - KC)$ to be stable.

VII. ADAPTIVE STATOR RESISTANCE AND ROTOR SPEED OBSERVATION

The rotor speed and the stator resistance are reconstructed using the model reference adaptive system (MRAS). The MRAS principle is based on the comparison of the outputs of two estimators. The first is independent of the observed variable named as model reference. The second is the adjustable one. The error between the two models feed an adaptive mechanism to turn out the observed variable.

In this work, the actual system is considered as the model reference and the observer is used as the adjustable one. The stator resistance and the rotor speed are built around the following adaptive mechanisms:

$$\hat{R} = -\mu' \int_0^t (e_d \hat{i}_d + e_q \hat{i}_q) dt \quad (17)$$

$$\text{with } \mu' = \frac{\lambda'}{L_s}; e_d = i_d - \hat{i}_d; e_q = i_q - \hat{i}_q$$

$$\hat{\omega}_r = K_p (i_d \hat{i}_q - \hat{i}_d i_q - \frac{\Phi_v}{L_s} e_q) + K_i \int_0^t (i_d \hat{i}_q - \hat{i}_d i_q - \frac{\Phi_v}{L_s} e_q) dt \quad (18)$$

Where K_p, K_i and μ' are the proportional and integral constants respectively. The tracking performance of the speed estimation and the sensitivity to noise are depending on

proportional and integral coefficient gains. The integral gain K_i is chosen to be high for fast tracking of speed. While, a low proportional K_p gain is needed to attenuate high frequency signals denoted as noises [9].

MRAS representation structure for identifying the rotor speed and the stator resistance simultaneously is given in Fig.10. The scheme consists of 2 models; reference and adjustable ones and an adaptation mechanism. The block reference model represents the actual system having unknown parameters values. The block adjustable model has the same structure of the reference one, but with adjustable parameters instead of the unknown ones. The block adaptation mechanism updates the adjustable model with the estimated parameter until satisfactory performance is achieved. The PMSM model was considered to be the reference model and we have used the Luenberger observer as adjustable model to obtain the estimated stator currents [10].

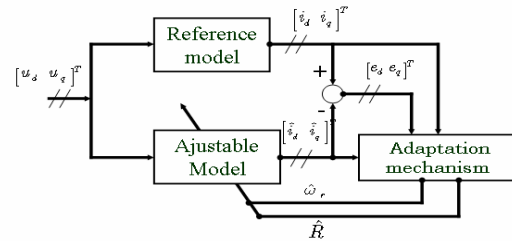


Fig.10 Block diagram of the MRAS observer

VIII. SIMULATION RESULTS AND DISCUSSION

The efficiency of the proposed control scheme has been verified based on an extensive simulation work under MATLAB/SIMULINK software package. Motor parameters used in simulations are given in table III .

The adaptive control algorithm for sensorless PMSM at variable step speed target under no load and with load applied has been tested. The effects of stator resistance variation are also considered.

In fact, after starting process without load $T_L=0$, a load torque of $T_L=5.5N.m$ is applied at 0.2s and at $t=0.8s$ after cancellation at 0.5s. The speed is inverted at $t=0.5s$. Simulation results are reported in Fig.11. The d and q axis stator currents responses indicate that the decoupling of the PMSM is established and ensured. For adaptive Luenberger observer method good dynamic response in speed without overshooting in starting and inversion, an influence at the inversion in currents is observed.

To investigate the behavior of the proposed sensorless control drives against stator resistance variation, a load torque of $T_L=5.5N.m$ is applied at 0.5s after starting process without load $T_L=0$ under deviation of stator resistance from its nominal value by 100% at $t=0.4s$. The obtained results are given in Fig.12. Errors between the real and the estimated speeds and also currents occur at a time of the load and resistance variation. But, these errors are maintained and there is no compensation.

To overcome the sensivity of the vector control algorithm against stator resistance variation, estimation and on line adjustment of the stator resistance in vector control algorithm is necessary to maintain the decoupling of the PMSM. The MRAS principle has been used to observe the stator resistance value. The obtained results with on line adjustment of the stator resistance are reported in Fig.13.

The system response converges to the model reference one. An error occurs at time of the stator resistance variation. It converges to zero thanks to the adaptive control algorithm. The d and q axis stator currents responses indicate that the decoupling of the PMSM is established and ensured despite of the stator resistance variation. This is because of the on line estimation and tuning of stator resistance in the vector control algorithm. The results show that the observed stator resistance follows exactly the real stator resistance, indicating the robustness of the proposed algorithm.

Fig. 14 shows simulation results under load with and without on line adjustment of the stator resistance. The steady state currents during high deviation of stator resistance without on line adjustment of the stator resistance show the last of decoupling. Moreover, one can notice from fig.14 (d) that when the resistance increases the speed drops and regulation performances are lost. But, the decoupling and the performances of the PMSM is maintained and ensured despite of the stator resistance variation in the case of on line adjustment of the stator resistance.

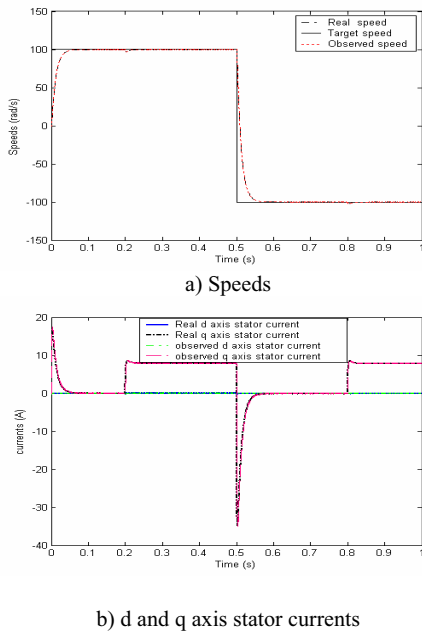


Fig.11 Simulation results under load and speed reverse

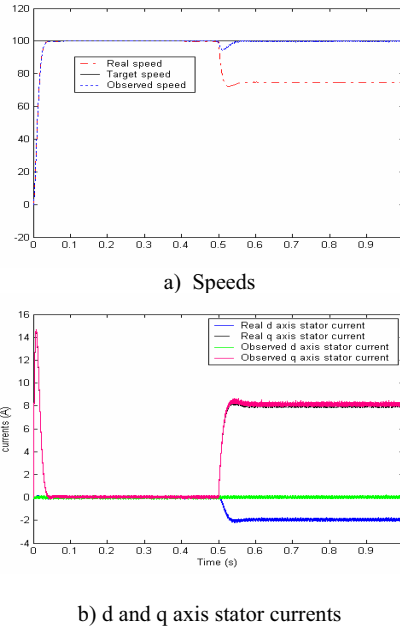
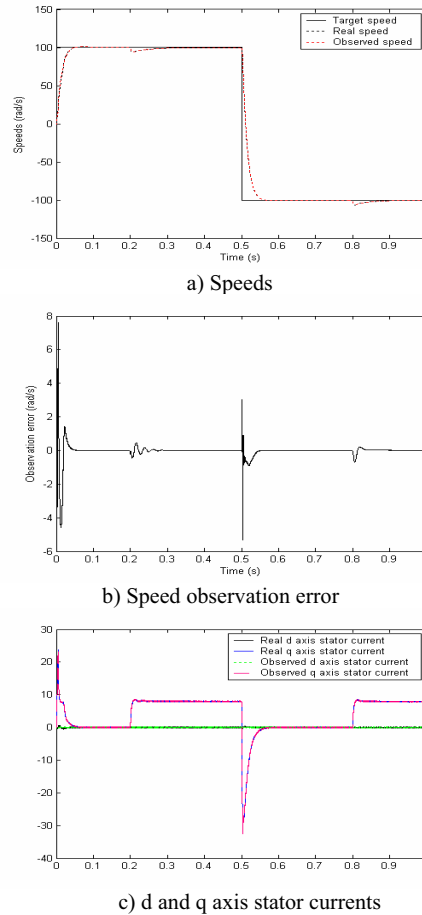
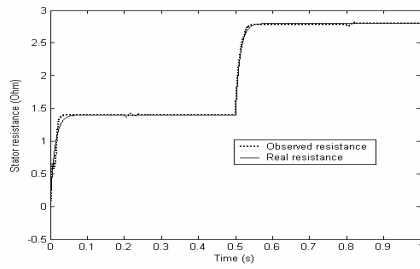


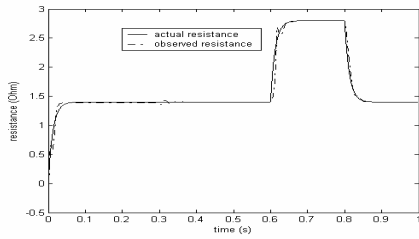
Fig.12 Simulation results under load and stator resistance variation



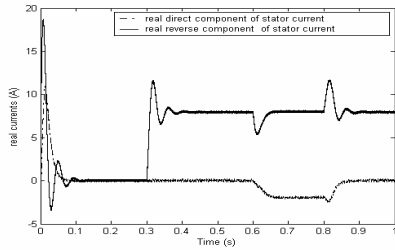


d) Observed and actual stator resistance

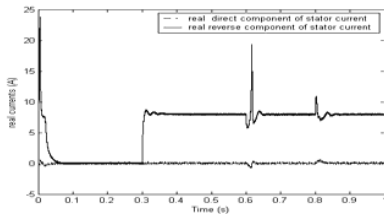
Fig.13 Simulation results under load and speed reverse with on line adjustment of the stator resistance



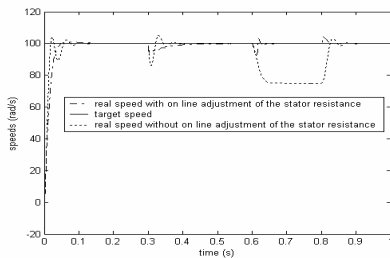
a) Observed and actual stator resistance



b) Real d and q axis stator currents without on line adjustment of the stator resistance



c) Real d and q axis stator currents with on line adjustment of the stator resistance



d) Real speeds

Fig.14 Simulation results under load with and without on line adjustment of the stator resistance

IX. CONCLUSION

In this paper, the synthesis of a sensorless Indirect Field Oriented Control of Permanent Magnet synchronous Motor based on adaptive Luenberger observer is presented. The adaptive with control algorithm for the rotor speed associated with fuzzy speed and current controllers show good performances under no load, load applied and against stator resistance variation. The influence of the stator resistance variation on the Indirect Field Oriented Control was eliminated by the proposed algorithm for the estimation and on line adjustment of the stator resistance. The validity of this algorithm has been verified by simulation under Matlab/Simulink environment.

Practical implementation of the proposed method is a subject of future follow up research work.

APPENDIX

TABLE III

THE PMSM CHARACTERISTIC PARAMETERS

| | |
|---------------|----------------------|
| Rated voltage | 220/380V |
| R | 1.4Ω |
| L_d | 6.6mH |
| L_q | 5.8mH |
| L_s | 6.6mH |
| Φ_v | 0.1546Wb |
| J | $0.00176N.m.s^2/rad$ |
| f | $0.000388 N.m.s/rad$ |
| p | 3 |

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Grouz Faten was born in 1984, Mars 22. An engineer diploma (Electrical and automation) in 2008, Graduated in April, 2009 with master degree (Automation and Intelligent Techniques). At present, she is a Ph.D candidate of Electrical Engineering Department. I'm trying to accomplish my Ph.D. thesis. Now, she is beginning her PhD research at National Engineering School of Gabès, University of Gabès with the title of "Fault Diagnosis and Isolation of a PMSM actuator".

Lassaâd Sbita was born in Tunis on April 05, 1962. He obtained the HDR on March 2008 in Electrical engineering from National Engineering School of Sfax, Tunisia. He works as Professor at the electrical-automatic genius department of the National Engineering School of Gabès, Tunisia. He is manager of the research Team on electric machine drives in the research Unit MACS-ENIG. His fields of interest include power electronics, machine drives, automatic control, modeling, observation and identification.