

# An adaptive high speed PMSM control for electric vehicle application

**Flah Aymen**

National School of Engineering of Gabes  
[flahaymening@yahoo.fr](mailto:flahaymening@yahoo.fr)

**Sbita Lassaâd**

National School of Engineering of Gabes

**Abstract:** *This paper deals with a new high speed direct torque control method applied on the permanent magnet synchronous motor. This high speed control algorithm is characterized by its efficiency and its adaptation to the motor parameters variations. Based on the field weakening principle and on the model reference adaptive system (MRAS), this algorithm is build. Where, the MRAS is used for online estimated the motor parameters variation and the field weakening for online generating the reference flux magnitude. The novel high speed control method, show the system good performances and its efficiency, especially in the losses power minimization.*

**Keywords:** PMSM, Adaptive high speed, power losses, DTC.

## 1. INTRODUCTION

Environmental and economic considerations are the major reasons for the development of electric vehicles and added to the easiness maintenance and the simplicity architecture, these lasts are more and more in uses. These vehicles performances are based on the motor type used. Effectively, numerous electrical motor are proposed for this application. Several works are studied and compared these lasts in order to define the best and efficient one that can be used in this application. In [1], Zhu was established a comparative study between, the Brushless DC motor, induction motor, switching reluctance motor and the permanent magnet synchronous motor. However, the Permanent Magnet Synchronous Motors (PMSM) drives are the most competitors to the other. Due to its superior advantages such as high efficiency, low inertia, high torque to current ratio, high power factor, smaller size, lower weight and almost no need for maintenance, makes it more preferable face to the other motors.

In the electrical vehicle applications, the vehicle can be operated at a variable speed running. Where, the motor speed control is extremely important. Effectively, many control strategy have been developed for improving the performance of the PMSM drives. The vector control (VC) technique, proposed by Hasse and Blaschke, is used in many applications interested to control the induction motor as presented by Harnefors in

[2] and Holtz in [3]. However, its dependence of a three PI controllers, present the method difficulties. Where, the design of the speed and currents regulators depends on exact mathematical models with accurate parameters.

The DTC technique is appeared after the VC strategy, its advantages as less machine parameter dependence, simpler implementation, quicker dynamic torque response and its good robustness, make it more advantageous to use this control strategy. Many works are proposed based on this last by Lorenz in [4], Boldea in [5] and Lascu [6]. These authors was discussed the DTC weakness as fluctuation problems. Therefore, many DTC strategies are proposed and numerous modifications are presented to improve the global performances, especially by Lascu in [6] and [7], where the torque pulsations are minimized. After compared these DTC methods, Lascu demonstrated the simplicity of the classical DTC based on the switching table. Started from this theory, other works are carried out to improve the performance of this last. Effectively, the stator flux locus is divided into twelve sectors instead of six, which all six active states will be used in each sector as presented in [8].

This last proposed DTC strategy, proved its efficiency in the induction motor speed and torque control and it performance in the losses power minimization as presented in [26]. Based on these advantageous, this strategy is used to control the PMSM. This control method uses the stator flux and electromagnet torque as reference inputs, for generating the desired stator voltage. Generally, the second input signal can be obtained by the speed controller. However, the first one must be calculated.

As our application will be running in the high speed mode, a stator flux magnetization is necessary. Therefore a field weakening bloc is essential for generating the required stator flux. This phenomenon is presented by many authors as Sneyers in [9], Johns in [10] and [11], by Lorenz in [12], by Harnefors in [13] and other specialist as Holtz and Sul in [14] and [15] respectively. The main idea of this approach consisting to, demagnetize the d\_axis armature reaction current  $i_d$ . Many field weakening methods are presented in the literatures as Morimoto approach described in her papers [16], [17] which he introduced the voltage and current converter limits in the analytical expression of the field weakening. Other theories are based on the stator current error and the actual speed like cited in

[18], [19]. However, the presented problems of all these approaches are appeared in the PMSM parameters variations due to temperature variation, vibrations or dust. Some authors like Schiferl and Lipo [20] are studied the influences of these parameter variations on the field-weakening performance, especially in a stator inductance variation terms. The latest work presented in [21], takes into account the motor resistance effect. But, these approaches are criticized for not considered all the motor parameters.

Therefore we propose in this work a new adaptive field weakening approach applied on the DTC strategy and take account any PMSM parameter variation, as permanent magnet, stator resistance and inductance. The adaptation mechanism is guaranteed by an online PMSM parameters estimation based on a model reference adaptive system (MRAS). The effectiveness of the proposed algorithm is shown in the field weakening working region. Where, with the new algorithm, this last can be moved proportionally to the PMSM parameters variations. In other hand, the results proved the importance of the proposed adaptive high speed algorithm in the copper losses minimization face to the non adaptive one.

This paper is organized as following: in section II a description of the PMSM control strategy is given. The section III, describe the proposed adaptive high speed algorithm. Where a simulation results demonstrate the effectiveness of the proposed algorithm in the field weakening zone movement. Section IV is designed for the discussion of the simulation results, where the importance of the adaptive field weakening algorithm is proved in the copper losses minimization in high speed range.

## 2. PMSM Control Strategy

The PMSM control devices can be operated with many control strategies. One can use field oriented control or direct torque control strategies. However, the necessity of a rapidly torque control make the second method more advantageous. The practical implementation of the proposed control strategy (DTC) is simple of use. To help the theoretical study we introduce a mathematical model of the proposed devices to be controlled. So, started from the nonlinear differential equations [22], [23]. The voltage expression can be presented in the system of equation (1).

$$\begin{cases} v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \\ v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \lambda_m \end{cases} \quad (1)$$

The stator flux expressions in the rotating (d, q) frame are given in (2).

$$\begin{cases} \lambda_d = L_d i_d + \lambda_m \\ \lambda_q = L_q i_q \end{cases} \quad (2)$$

The electromechanical torque can be expressed in (3), if the PMSM is salient. However, for the non salient case,  $L_d=L_q=L_s$  then the expression depends only on magnet flux and quadrature stator current.

$$T_e = \left(\frac{3}{2}\right) \left(\frac{P}{2}\right) (\lambda_d i_q - \lambda_q i_d) \quad (3)$$

The PMSM-DTC drive is carried out by hysteresis control of stator flux and torque that directly select one of the six non-zero and two zero discrete voltage vectors for the inverter [24]. The selection of the voltage vectors is made to restrict the motor stator flux and torque errors within the hysteresis band and obtain the fastest torque response [25]. The selection of the voltage vectors in conventional DTC is based on the output errors produced by the torque and the flux hysteresis controllers ( $\tau_f$  and  $\tau_T$ ) and is provided as inputs to a switching table [26].

The stator flux expression is derived from (4), using only the measured stator voltages and currents [28].

$$\vec{\lambda}_s = \int \left( \vec{v}_s - R_s \vec{i}_s \right) dt \quad (4)$$

This equation is the foundation for implementing the flux estimator. It may be implemented directly, or approximated by various methods to avoid integrator drift [26]. The amplitude and angular position of the stator flux vector must be known so that the DTC can chose between an appropriate set of vector depending on the flux position and amplitude.

$$\begin{cases} |\lambda_s| = \sqrt{\lambda_\alpha^2 + \lambda_\beta^2} \\ \theta_s = \tan^{-1} \left( \frac{\lambda_\beta}{\lambda_\alpha} \right) \end{cases} \quad (5)$$

In classical DTC, there are two states per sector that present a torque ambiguity. In fact, they are not used. It can be seen in the first sector that the vectors V1 and V4, are not used in the classical DTC because they can increase or decrease the torque at the same sector depending on if the position is in its first 30 degrees or in its second one. It seems a good idea that if the stator flux locus is divided into twelve sectors instead of just six, all six active states will be used per sector. Consequently, it is arisen the idea of the twelve sectors DTC. This novel stator flux locus is illustrated in Fig.1.

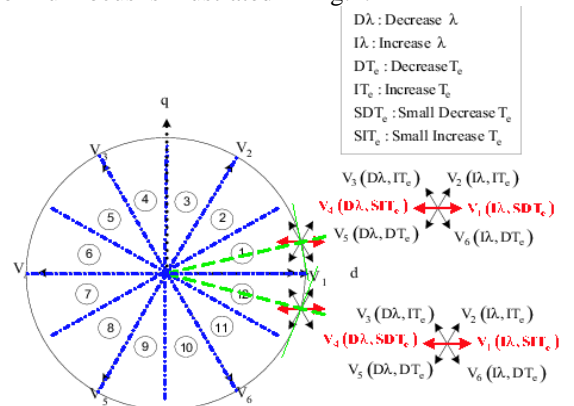


Fig. 1. The 12 sectors DTC strategy

It has to be introduced the idea of small torque increase instead of torque increase, mainly due to the fact that the tangential voltage vector component is very small. Consequently its torque variation will be small as well.

### 3. Adaptive High Speed Control Algorithm

For operating at high speed region, a specific control algorithm, based on flux weakening technique, is applied [9]. 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. In the DC motor this action is simple. However, in the PMSM, the flux is mainly produced by the rotor magnet ( $\lambda_m$ ). Refers to the mathematical flux expressions, at the rated speed the direct stator current  $i_d$  is equal to zero, but if the desired speed is above the based one, the idea refers to minimize the direct stator current  $i_d$ , where its value is reduced to the negative values  $i_d < 0$ . When performing this control, the currents and voltages are kept below a maximum value. The maximum of current and voltage are usually set by the inverter [17] and the limit system of equations, take into account the maximum voltage and maximum current as expressed in (6) [16]. The values  $I_{max}$  and  $V_{max}$  are respectively the maximum inverter phase-current and phase-voltage amplitudes.

$$\begin{cases} I_d^2 + I_q^2 \leq I_{max}^2 \\ V_d^2 + V_q^2 \leq V_{max}^2 \end{cases} \quad (6)$$

Therefore, the principle of field weakening can be described by two circles in the stator current reference, as illustrated in Fig. 2 [30]. Two types of circles are then presented. The first is for the current limitation condition. However, the circle center is zero and the radius is the maximum current. The second type describes the circle voltage limit. The radius is proportional to the speed inverses. Effectively, when the speed increases, the voltage circle radius decreases. The voltage circle center depends on the PMSM parameters.

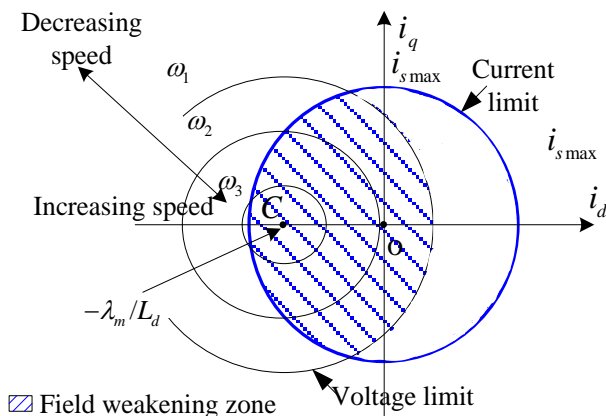


Fig. 2. Field weakening strategy diagram

In the electrical vehicle applications, many causes can modify the motor parameters. One can depict the temperature that affects the stator resistance and especially the permanent magnet values. Where, their values can increase or decrease above the rated one, respectively. The mathematical expression related the temperature factor, the stator resistance and the magnet flux value can be expressed respectively by equation (7) and (8).

$$\begin{cases} R_s(T) = \rho(T) \frac{l_{bob}}{S_{bob}} \\ \rho(T) = \rho_0 [1 + \alpha_c (T - T_0)] \end{cases} \quad (7)$$

$$\begin{cases} B_a(H_a, T) = B_r(T) + \mu_0 \mu_r H_a \\ B_r = B_{r_0} [1 - \Delta B_r (T - T_0)] \end{cases} \quad (8)$$

This variation can modify the flux weakening zones. The set of figures Fig. 3 to Fig. 5 demonstrate these effects.

Some author, neglect the stator resistance variation on the field weakening algorithm, when the speed variation is above the rated one as presented in [16]. However, this variation can influence on the field weakening zone. In Fig. 3, is taking into account the two field weakening algorithm. The normal one proposed by Morimoto where he neglects the stator resistance parameter and the proposed one which considers it. Zone B presents the Morimoto field weakening zone. Zone A the field zone with the present field weakening algorithm. And Zone C, presents the field weakening zone when a stator resistance variation is applied. The same tests are applied on the field weakening zones, if a stator inductance or permanent magnet flux variation is applied, respectively in Fig. 4 and Fig. 5. Zone B presents the field weakening zone if these variations are introduced for the proposed field weakening algorithm. The corresponding PMSM parameters variations are illustrated in Fig. 9, 10 and 11.

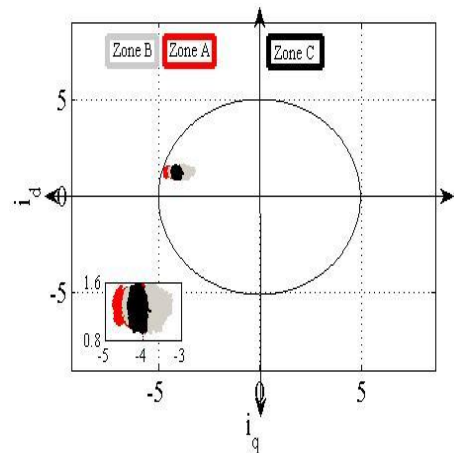


Fig. 3. Field weakening Zone for stator resistance variation

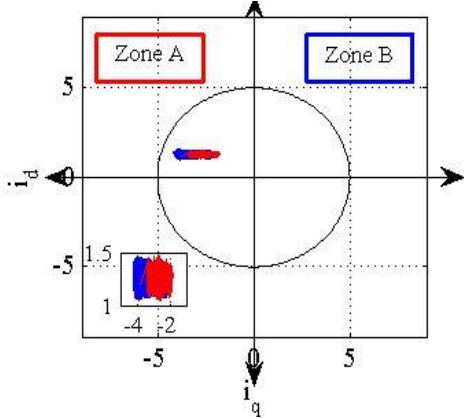


Fig. 4. Field weakening Zones for stator inductance variation

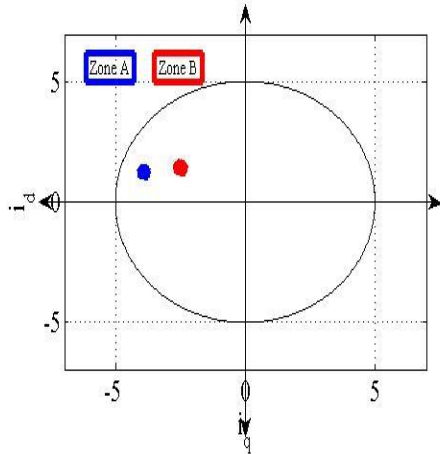


Fig. 5. Field weakening Zone for permanent magnet flux variation

So the idea refers to illustrating an adaptive field weakening (AFW) which is adjusted if any variations of stator resistance, inductance or permanent magnet flux, occur.

Started from the tow maximum limit conditions on the inverter, maximum voltage and maximum currents, and tacked account that the quadrature stator current is obtained from the speed controller [30]. The reference direct stator current can be then obtained from (9).

$$V_{\max}^2 = R_s^2 [i_q^2 + i_d^2] + 2R_s i_q \omega \lambda_m + \omega L_s^2 i_q^2 + [\omega L_s i_d + \omega \lambda_m]^2 \quad (9)$$

The limit condition on the stator current if the quadrature component is equal to zero becomes:

$$i_{d \text{ lim}} \Big|_{i_q=0} = \frac{-\left(2L_d \omega^2 \lambda_m\right) - \sqrt{4V_{\max}^2 \left[R_s^2 + \omega^2 L_d^2\right] - 4\omega^2 R_s^2 \lambda_m^2}}{2\left(R_s^2 + \omega^2 L_d^2\right)} \quad (10)$$

And the direct stator current reference is:

$$i_d^* = \frac{\sqrt{\frac{V_{\max}^2 - R_s^2 I_{\max}^2 - [\omega L_s i_q]^2 - 2R_s i_q \lambda_m \omega}{\omega^2}} - \lambda_m}{L_s} \quad (11)$$

In (11), all the PMSM parameters are tacked account. So PMSM parameters estimation is needed. The model reference adaptive system (MRAS) estimator is

developed in order to identify the PMSM parameters, based on the POPOV stability theory [28]. The proposed estimator needs only the online measurement of current, voltage, and rotor speed to effectively estimate the stator resistance and inductance and the rotor flux linkage simultaneously. By choosing d and q components of the stator current as variable states, the PMSM state equation takes the following form:

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \end{bmatrix} = \begin{bmatrix} -\tau & \omega \\ -\omega & -\tau \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} + \begin{bmatrix} 0 \\ -e_f \end{bmatrix} \quad (12)$$

For a surface PMSM, non saliency effect is  $L_d=L_q=L_s$ .  $i_d, i_q, u_d, u_q$  are the d and q components of the stator currents and voltages.

$$\text{And } \begin{cases} c = 1/L_s \\ ef = \omega \lambda_m / L_s = \omega I_f \\ \tau = R_s / L_s \end{cases}$$

The adjustable parameter state equation is given by:

$$\begin{bmatrix} \hat{\dot{i}}_d \\ \hat{\dot{i}}_q \end{bmatrix} = \begin{bmatrix} -\hat{\tau} & \omega \\ -\omega & -\hat{\tau} \end{bmatrix} \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} + \begin{bmatrix} \hat{c} & 0 \\ 0 & \hat{c} \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \hat{I}_f \end{bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \begin{bmatrix} \hat{i}_d - i_d \\ \hat{i}_q - i_q \end{bmatrix} \quad (13)$$

G is the correction gain matrix to be chosen so as to achieve pre-specified error characteristics, where  $k_1, k_2$  are two limited positive real's. The problem of the system stability can be resolved by the application of the POPOV stability theories, where two necessary conditions must be satisfied [22], [29] :

The transfer function matrix of the linear forward block must be real and strictly positive, and according to [20] the gain matrix G presented in (13), assure this condition. The nonlinear feedback block meets POPOV

integral inequations presented by:  $\int_0^t w^T edt \geq -\gamma^2$ ,

where  $\gamma^2$  is a positive constant for any t.

So the expressions of the adaptive parameters can be written as [28]:

$$\frac{\hat{R}_s}{L_s} = -\left(k_{pr} + \frac{k_{ir}}{s}\right) \left(\hat{i}_d e_d + \hat{i}_q e_q\right) + \frac{\hat{R}_s}{L_s}(0) \quad (14)$$

$$\frac{1}{L_s} = \left(k_{pl} + \frac{k_{il}}{s}\right) (u_d e_d + u_q e_q) + \frac{1}{L_s}(0) \quad (15)$$

$$\frac{\hat{\lambda}_m}{L_s} = -\left(k_{pf} + \frac{k_{if}}{s}\right) (\omega e_q) + \frac{\hat{\lambda}_m}{L_s}(0) \quad (16)$$

Then the adjustable direct reference stator current is given as:

$$i_d^* = \sqrt{\frac{V_{\max}^2 - \hat{R}_s^2 I_{\max}^2 - [\omega \hat{L}_s i_q]^2 - 2\hat{R}_s i_q \hat{\lambda}_m \omega}{\omega^2}} - \hat{\lambda}_m \quad (17)$$

Finally, the proposed field weakening algorithm can be formed, and the Fig.6 illustrates the proposed algorithm. After obtained the quadrature reference stator current from the speed controller, the direct adaptive reference

one can be obtained under the maximum voltage and maximum current conditions. After compared the desired speed value and the reference one, with the switching bloc, we can generate the direct reference stator current. The direct stator current error will be tacked as an input for the PI controller for generating the direct reference stator flux. Then, with the quadrature reference flux the reference stator flux is obtained and applied on the global control algorithm.

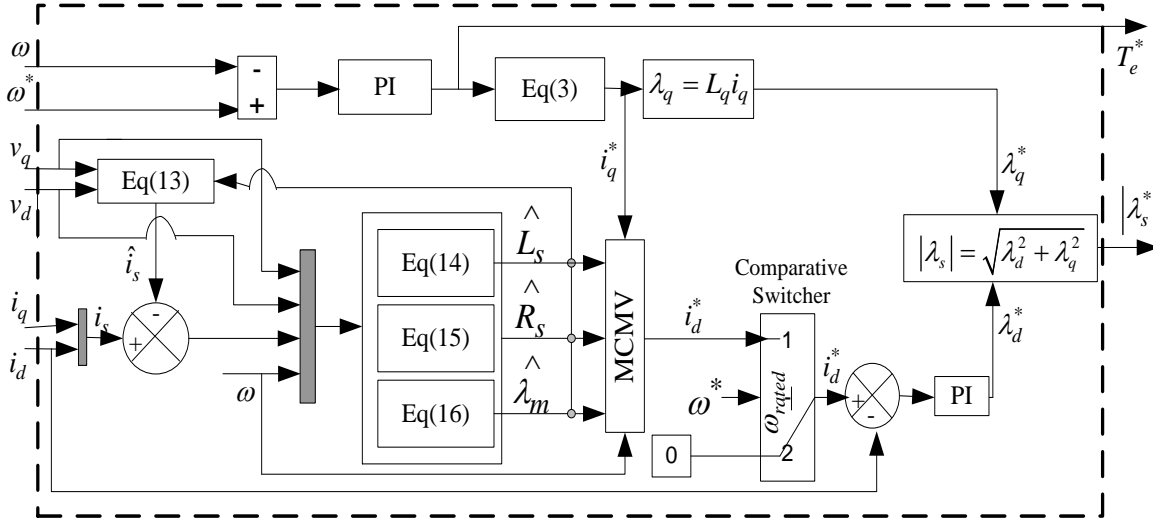


Fig. 6. The adaptive high speed control algorithm

#### 4. Simulation Results

To verify the effectiveness of the proposed high speed control algorithm in the DTC twelve sectors strategy for controlling the PMSM. A digital simulation based on Matlab/Simulink software package has been carried out. The PMSM characteristics are given in table.1. After according the different components in the Matlab/Simulink environment, the effectiveness of the proposed high speed algorithm in the copper losses minimization will be approved. The global control scheme is illustrated in Fig. 7

The principle of this application tends to simulate the electric vehicle compartment. The motor started with a maximal load torque.  $T_1=1.5N.m$ , if the given speed is under the rated speed (2500) and decrease to  $T_1 = 1.2N.m$  if the given speed is increasing up the rated speed motor. As a robustness test of the global control scheme, an abrupt load torque variation is applied in the rated, at  $t=0.4sec$ , and over the rated speed, at  $t=0.8sec$ . The obtained results show the effectiveness of the proposed control scheme.

In Fig.8 (a) to Fig.8 (e), we demonstrate the behavior PMSM results as speed, electromagnet torque, stator current and magnet flux. The obtained results are illustrated under a variable given speed. As a ramp form, the given speed started from 0rpm to 2000 rpm then from 2000rpm to 3500rpm. The filed weakening result can be illustrated in the Fig.8. (d) and Fig. 8. (e).

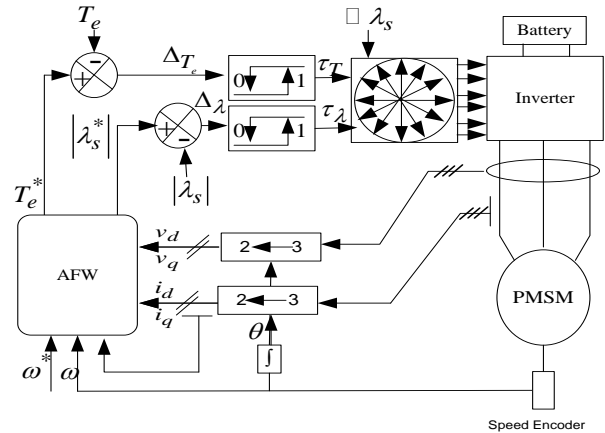


Fig. 7. Block diagram of the proposed DTC-High speed-PMSM overall control system

Where, the negative evolution of the direct stator current and the flux minimization result at the high speed region verify the field weakening principle.

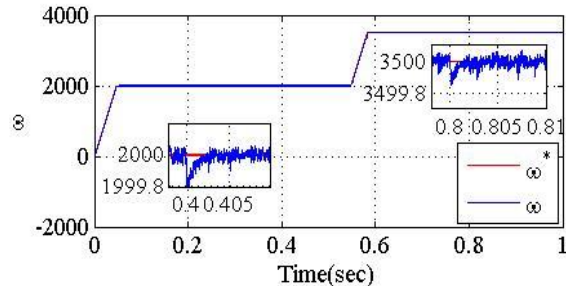


Fig. 8. (a) Speed results

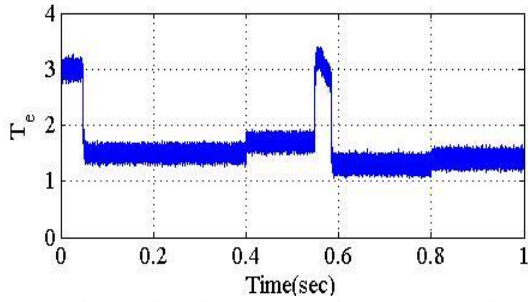


Fig. 8. (b) Electromagnetic Torque results

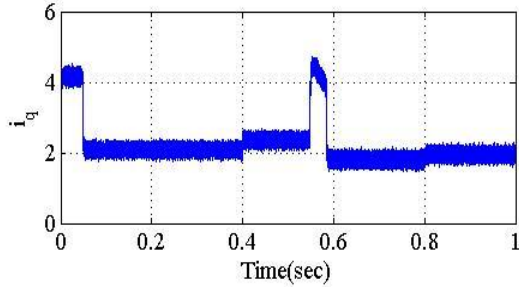


Fig. 8. (c) Quadrature Stator currents results

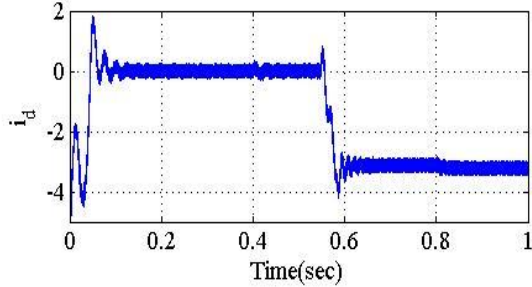


Fig. 8. (d) Direct Stator currents results

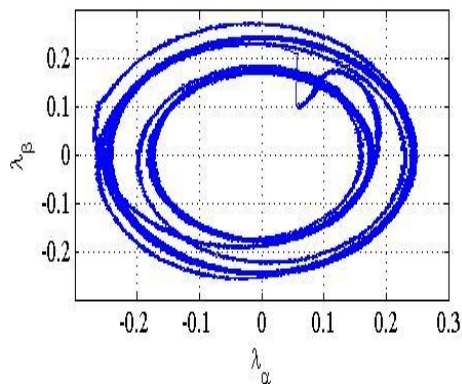


Fig. 8. (e) Field weakening trajectory in the  $\alpha$ - $\beta$  flux frame

After verified the overall high speed control scheme performance under a wide speed range. The proposed algorithm will be tested. Where, PMSM parameters variations are applied in order to show the adaptive high speed control algorithm performance in terms of adaptation and totally copper losses.

Fig. 9, 10 and 11, show the estimated stator resistance, inductance and permanent magnet flux variations and the corresponding copper losses in the normal field weakening (NFW) algorithm and in the proposed one (AFW). The

effectiveness of the proposed high speed control algorithm is proved, where the losses power value is minimized in the cases of stator inductance and permanent magnet flux variations, especially in the high speed mode.

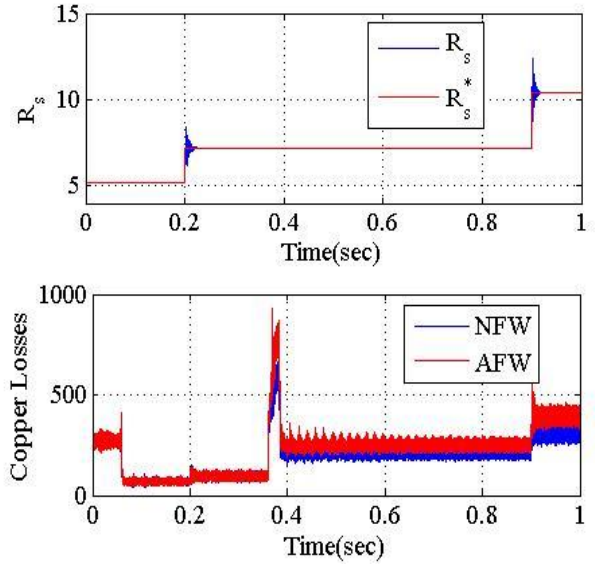


Fig. 9. Power Losses for stator resistance variation

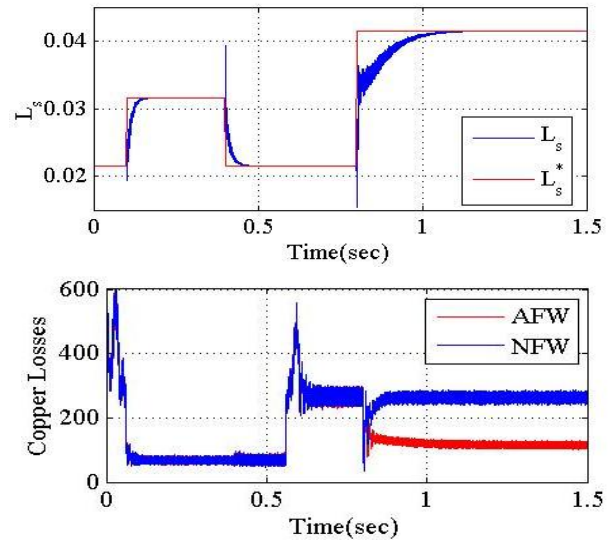
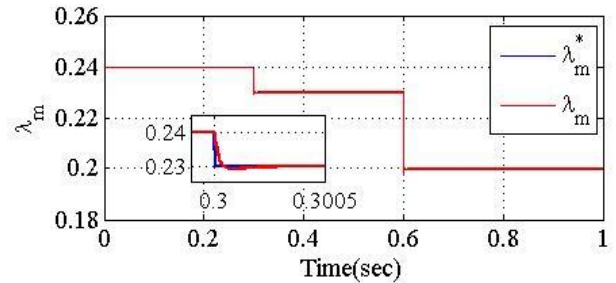


Fig. 10. Power Losses for stator inductance variation



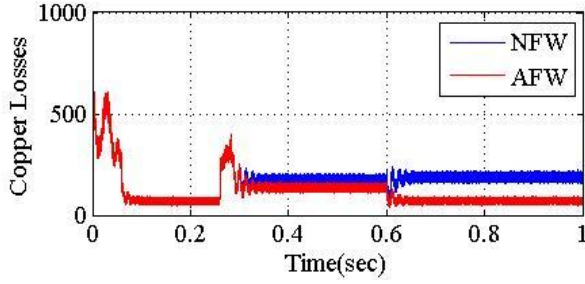


Fig. 11. Power Losses for permanent magnet flux variation

## 5. CONCLUSION

In this paper a novel adaptive high speed control algorithm is carried out. Based on the MRAS estimator and the maximum limitation of current and voltage, the planned algorithm is build. The importance of the proposed algorithm is demonstrated for the minimization of the copper losses. A comparative study between the adaptive field weakening algorithm and the normal one verify the importance of the AFW. A simulation results demonstrate the effectiveness and the robustness of the global control scheme with the gives algorithm.

Power	400W
Rated Current $I_{rated}$	2A
Maximum Current $I_{max}$	5A
Rated Speed $\omega_{rated}$	2500rpm
Rated Torque $T_{rated}$	1.5N.M
Stator Inductance $L_s$	0.00215 H
Stator resistance $R_s$	5.2 $\Omega$
Permanent flux $\lambda_m$	0.24Wb
Inertia factor J	85e-6kg.m <sup>2</sup>

Table 1. PMSM parameters and rated characteristics

## APPENDIX

$v_d, v_q$	Direct and quadrature stator voltages
$\lambda_d, \lambda_q$	Direct and quadrature stator flux
$i_d, i_q$	Direct and quadrature stator currents
$L_d, L_q$	Direct and quadrature stator inductances
$\omega$	Mechanical speed
$\lambda_m$	Magnet flux
$R_s$	Stator resistance
$T_l$	Load torque
P	Poles number
J	Rotor inertia coefficient
AFW	Adaptive Field Weakening
NFW	Normal Field Weakening
MCMV	Maximum Current Maximum Voltage
$K_p, K_i$	PI-MRAS parameters
$\alpha_c$	Copper Coefficient
$T, T_0$	Temperature coefficient
$S_{bob}$ and $L_{bob}$	Coil Section and Coil Length
$\Delta B_r$	Remanent induction variation
$H_a$	Magnetique Field
$B_a$	Magnetique induction in Temperature $T_a$
$B_{ra}$	Remanent induction
$\mu_{ra}$	Permeability coefficient

## REFERENCES

1. Z. Q. Zhu, D. Howe, Electrical machines and drives for electric vehicle, hybrid and fuel cell vehicles, Proceeding of IEEE Trans. Vol. 95, n. 4, 2007, pp. 746-765.
2. O. Wallmark, L. Harnefors, O. Carlson, Sensorless control of PMSM drives for hybrid electric vehicles, IEEE 35th Annual Power Electronics Specialists Conference, Vol.4, 2004, pp. 4017 – 4023.
3. J. Holtz, T. Thimm, Identification of the machine parameters in a vector controlled induction motor drive, Conference Record of the 1989 IEEE Industry Applications Society Annual Meeting, 1989, pp. 601-606.
4. T. R. Obermann, Z. D. Hurst, R. D. Lorenz, Deadbeat-direct torque & flux control motor drive over a wide speed, torque and flux operating space using a single control law, IEEE Energy Conversion Congress and Exposition, 2010, pp. 215 – 222.
5. I. Boldea, C. I. Pitic, C. Lascu, G-D. Andreescu, L. Tutelea, F. Blaabjerg, P. Sandholdt, DTFC-SVM motion-sensorless control of a PM-assisted reluctance synchronous machine as starter-alternator for hybrid electric vehicles, IEEE Transactions on Power Electronics, Vol. 21, n. 3, 2006, pp. 711-719.
6. C. Lascu, I. Boldea, F. Blaabjerg, A modified direct torque control for induction motor sensorless drive, IEEE Transactions on Industry Applications, Vol.36, n.1, 2000, pp.122-130.
7. C. Lascu, I. Boldea, F. Blaabjerg, Direct torque control of sensorless induction motor drives: a sliding-mode approach, IEEE Transactions on Industry Applications, Vol. 40, n. 2, 2004, pp. 582-590.
8. G. S. Buja, M. P. Kazmierkowski, Direct torque control of PWM inverter fed AC motors a survey, IEEE Trans. Ind. Electron, Vol. 5 n. 4, 2004, pp. 744–757.
9. B. Sneyers, D.W. Novotny, T.A. Lipo, Field-weakening in buried permanent magnet AC motor drives, IEEE Transactions on Industrial Applications, Vol. 21, 1985, pp. 398 407.
10. S. R. Macminn, T. M. Jahns, Control techniques for improved high-speed performance of interior PM synchronous motor drives, IEEE Transactions on Industry Applications, Vol.27, n. 5, 1991, pp. 997-1004.
11. A. M. EL-Refaie, T. M. Jahns, Optimal flux weakening in surface PM machines using fractional-slot concentrated windings IEEE Transactions on Industry Applications, Vol.41, n.3, 2005, pp.790-800.
12. F. Briz, A. Diez, M. W. Degner, R.D. Lorenz, Current and flux regulation in field-weakening operation [of induction motors] ,The Thirty-Third IAS Annual Meeting IEEE Industry Applications Conference, Vol.1, 1998, pp. 524-531.

13. L. Harnefors, K. Pietilainen, L. Gertmar, Optimum-seeking field weakening control of induction motor drives Eighth International Conference on Power Electronics and Variable Speed Drives, 2000, pp. 176 – 181
14. M. Wlas, H. Abu-Rub, H. J. Holtz, Speed sensorless nonlinear control of induction motor in the field weakening region, 13th Power Electronics and Motion Control Conference, 2008, pp. 1084 – 1089.
15. Kim, S.-H.; Sul, S.-K.; Park, M.-H, Maximum torque control of an induction machine in the field weakening region, Conference Record of the 1993 IEEE Industry Applications Society Annual Meeting, 1993, pp. 401-407.
16. S. Morimoto, Y. Takeda, T. Hirasu Expansion of operating limits for permanent magnet motor by current vector control considering inverter capacity, IEEE Transaction. Industry Application, Vol. 26, n. 5, September/October, 1990, pp. 866-871.
17. S. Morimoto, Y. Takeda, T. Hirasu ,Flux Weakening Control Method for Surface Permanent Magnet Synchronous Motors, IPEC. Tokyo'90, 1990, pp. 942-949.
18. Y. Sozer, D. A.Torrey, Adaptive Flux Weakening Control of Permanent Magnet Synchronous Motors, IEEE Conf. 1998 pp. 475–482.
19. Z .Q. Zhu, Y. S. Chen, D. Howe, Online Optimal Flux Weakening Control of Permanent Magnet Brushless AC Drives, IEEE Transaction Industry Application, Vol. 36, n. 6, 2000, pp. 1661- 1668.
20. R.F. Schiferl, T.A. Lipo, Power capability of salient pole permanent magnet synchronous motor in variable speed drive applications, IEEE Transactions on Industrial Applications, Vol. 26, 1990, pp. 115 123.
21. M. Tursini, E. Chiricozzi, R. Petrella, Feedforward Flux- Weakening Control of Surface- Mounted Permanent-Magnet Synchronous Motors Accounting for Resistive Voltage Drop, IEEE Transaction. Industrial. Electronic, Vol. 57, n. 1, Jan. 2010, pp.440-448.
22. A. Quntao, L. Sun, On line parameter identification for vector controlled PMSM drives using adaptive algorithm, IEEE Vehicle power and propulsion conference (VPPC), 2008.
23. X. Junfeng, X. Jiangping, A new method for permanent magnet synchronous machines with observer, IEEE power electronics specialists Conference, 2004.
24. T. J. Vyncke, R. K. Boel, J. AMelkebeek, Direct Torque Control of Permanent Magnet Synchronous Motors, 3RD IEEE Benelux Young Researchers Symposium in Electrical Power Engineering, n. 28, 2006, pp. 27–28.
25. J. Habibi, S. Vaez-Zadeh, Efficiency Optimizing Direct Torque Control of Permanent Magnet Synchronous Machines, Proc. IEEE Power Electronics Specialists Conference (PESC), 2005, pp. 759–764.
26. M. Messaoudi, H. Kraiem, M. Ben Hamed, L. Sbita, M. N. Abdelkrim, A Robust Sensorless Direct Torque Control of Induction Motor Based on MRAS and Extended Kalman Filter, Leonardo Journal of Sciences (LJS), Academic Direct, Vol. 7, 2008, pp. 35-56.
27. K. E. Quindere, E. F. Ruppert, M. E Oliveira, Direct torque control of permanent magnet synchronous motor drive with a three level inverter, 37th IEEE Power Electronics Specialists Conference, 2006, pp. 1–6.
28. A. Flah, L. Sbita, M. Ben hamed, Online MRAS-PSO PMSM parameters estimation, IREMOS, Vol. 4. n. 3, 2011, pp. 980-987.
29. L. Kan, Q. Zhang, J. Shen, S. Paul, Comparison of two novel MRAS strategies for identifying parameters in permanent magnet synchronous motors, International Journal of Automation and Computing, Vol. 3, 2010, pp. 516- 524.
30. A. Flah, H. Kraiem and L.Sbita Robust high speed control algorithm for PMSM sensorless drives”, IEEE 9th International Multi-Conference on Systems, Signals & Devices, SSD 2012, pp.1-6.