A new adaptive high speed control algorithm used for a FOC or a DTC PMSM drive strategies

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Abstract—This paper present a new adaptive high speed control algorithm (AHSC) for the permanent magnet synchronous motor (PMSM) drives. This AHSC algorithm has been built using the Model Reference Adaptive System (MRAS) and referring to the fed inverter variables limitation. The proposed control technique is mathematically formulated and implemented in the two conventional motor control strategies such as the Field Oriented Control (FOC) in one hand and the Direct Torque Control (DTC) on the other hand. The proposed AHSC is tested through computer simulation using MATLAB/ Simulink, where the system efficiency and robustness is verified for a wide speed range and under the two cited drive strategies. The obtained simulations results are satisfactory and confirmed the usefulness of the overall proposed control algorithm.

List of Symbols

AHSC  Adaptive high speed control
$v_{dq}, v_{dq}$  Direct and quadrature stator voltage
$\lambda_{dq}, \lambda_{dq}$  Direct and quadrature stator field
$i_{dq}, i_{dq}$  Direct and quadrature stator current
$L_{dq}, L_{dq}$  Direct and quadrature stator inductance
$L_s$  Stator inductance
$\lambda_m$  Magnet flux
$R_s$  Stator resistance
$T_t$  Load torque
$P$  Poles number
$J$  Rotor inertia coefficient.

I. INTRODUCTION

The permanent magnet synchronous motor (PMSM) is the most popular in the traction and electrical vehicle applications and in the generator mode especially in the wind turbine sector. Due to its superior advantages face to the other motor such as induction and reluctance motors; the high efficiency, low inertia, high torque to current ratio, high power factor and almost no need for maintenance, and especially for its smaller size, make this motor type the most adapted for high performance applications [1]. Generally, these applications can operate the motor in a speed value higher than the nominal one, where this phenomenon is commonly called the high speed or field weakening modes.

Effectively, the problem occurring in this speed region is the required high performances and efficient operating mode. The basic idea refers to operate the motor as a DC one, where the field weakening phase is naturally operated. But, in the PMSM, the rotor flux cannot be controlled due to the rotor permanent magnet. Therefore, the researchers are extremely dealing to work for resolving this problem details.

The conventional PMSM control strategies as the FOC and the DTC basic drives which are becoming very popular and manufactured due to their advantages and effectiveness, as presented in [2] and [3]. Generally, the speed reference is given to the control algorithm target and this last generates the desired stator voltage. However, in the FOC strategy, the direct stator current must be also given as another reference input signal [2]. In the standard applications, this second input signal is always fixed to zero. However, in this case, the high speed mode is unsupported and the maximum speed can be touched is the rated one. So, refers to the DC motor principle, the idea is to decrease the total flux by decreasing the direct stator current to the negative region. However, this direct stator current decrease must be also controlled for the motor parameters and the inverter security [4]. Similarly, in the DTC method, the second reference input signal must be the reference stator flux. This input signal must be generated according to the high speed operating mode and the motor and inverter safety [5].

In the literature, the high speed control algorithm is build based on the inverter constraints as the maximum speed and voltage. Morimoto, in his papers [4], [5] and [6], was considered these constraints in proposed high speed control algorithm.

The proposed Morimoto high speed control algorithm weakness is the PMSM parameters variation influence. Where, in the real applications, as the electrical vehicle, many parameters as temperature, dust or vibrations can influence on the PMSM parameters [7] that effect on the field weakening zone. Therefore, an adaptive high speed control algorithm is build regarding all these PMSM parameters variation and guarantees the components safety, is extremely necessary in this application.

In this paper, this problem is resolved and an adaptive high speed control (AHSC) algorithm is proposed. Based on the MRAS estimator and the Morimoto constraints, this algorithm is build and implemented in the two conventional control strategies, DTC and FOC, where two control schemes are given.

This manuscript is organized as fellow. After a general introduction section, the second one is designed for the
MRAS estimator and the third is for describing the high speed principle. The fourth part investigates the implementation of the HSCA in the FOC strategy and the sixth part for the DTC one. Then, the simulation results are presented and discussed and finally the conclusion is presented.

II. MRAS ESTIMATOR

The model reference adaptive system (MRAS) estimator is developed to identify the PMSM parameters, based on the POPOV stability theory. The proposed estimator needs only the online measurement of current 'i', voltage 'v', and rotor speed 'ω' to estimate the stator resistance 'Rs', inductance 'Ls' and the rotor flux linkage 'λm' simultaneously. Started from equations (1), (2) and (3), the electrical, the electromagnetic torque ‘Te’ and the mechanical PMSM equations are respectively [8].

\[
\begin{align*}
    v_d &= R_s i_d + L_s \frac{di_d}{dt} - ωL_m i_q \\
    v_q &= R_s i_q + L_s \frac{di_q}{dt} + ωL_m i_d + ω\lambda_m \\
    T_e &= \frac{3}{2} \left[ \frac{P}{J} \left( \lambda_d i_q - \lambda_q i_d \right) \right] \\
    \lambda_d &= L_d i_d + \lambda_m \\
    \lambda_q &= L_q i_q \\
    (T_e - T_f) &= \frac{P}{2} \left( J \frac{d\omega}{dt} + f \omega \right)
\end{align*}
\]

The stator current components as state variables in the d, q reference frame are expressed in (4).

\[
\dot{X} = AX + BU + C
\]

Where: \( A = \begin{bmatrix} -\tau & \omega \\ -\omega & -\tau \end{bmatrix} \), \( B = \begin{bmatrix} c \\ 0 \end{bmatrix} \), \( C = \begin{bmatrix} 0 \end{bmatrix} \);

\[
\begin{align*}
    X &= \begin{bmatrix} i_d \\ i_q \end{bmatrix}^T \\
    U &= \begin{bmatrix} v_d \\ v_q \end{bmatrix}^T \\
    c &= \frac{1}{L_s} \\
    e_f &= \omega \frac{\hat{\lambda}_m}{L_s} = ωI_f \\
    \frac{1}{\tau} &= \frac{L_d}{R_s}
\end{align*}
\]

The adjustable parameter state system is given by (5):

\[
\begin{align*}
    \dot{\hat{X}} &= \hat{A} \hat{X} + \hat{B} U + \hat{C} + G(\hat{X} - X) \\
    \hat{A} &= \begin{bmatrix} -\tau & \omega \\ -\omega & -\tau \end{bmatrix} \hat{B} = \begin{bmatrix} c \\ 0 \end{bmatrix} \hat{C} = \begin{bmatrix} 0 \\ \omega I_f \end{bmatrix} \\
    \hat{G} &= \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}
\end{align*}
\]

G represents the correction gain matrix to be chosen so as to achieve pre-specified error characteristics, where k1 and k2 are two limited positive real.

By subtracting the adjustable parameter system (5) from the state system (4), the result is defined in equation (6).

\[
\dot{e} = \Delta A e + \Delta B U + \Delta C + G e
\]

From (6) is decomposed a feed forward linear model “(A+G)” and a non linear feedback system “w” as expressed in (7).

\[
e = (A + G)e + w
\]

Based on the POPOV stability theory as presented in [9] and [10], the study of the system stability can be resolved.

After checking the two stability clauses and especially by decompressing the second POPOV condition the adaptive parameters equations are expressed in (8). Where kp, ki are the PI parameters.

\[
\begin{align*}
    \frac{\lambda_m}{L_s} &= -\left( k_p + \frac{k_i}{s} \right) (i_d e_d + i_q e_q) + \frac{R_s}{L_s} (0) \\
    \lambda_m &= -\left( k_p + \frac{k_i}{s} \right) (\omega e_q) + \frac{\lambda_m}{L_s} (0)
\end{align*}
\]

III. ADAPTIVE HIGH SPEED CONTROL ALGORITHM

The constant flux produced by the rotor magnet \( \lambda_m \) characterizes the PMSM motor. Refers to the flux equations presented in (2), the total flux decrease is possible only if the direct stator current is controlled. Because the stator inductance \( L_s \) and the flux \( \lambda_m \) are constant and the quadratic stator current is proportionally to the load torque. At a rated speed range, the direct stator current is fixed to zero, so the idea, in the high speed, is to reduce the total flux by decreasing the direct stator current to the negative region.

But, it is safety to not undergo a limit decreasing value which avoids the machine demagnetization problems.

Refers to Morimoto limitation [5], the idea is to follow the system of equation presented in (9).

\[
\begin{align*}
    I_d^2 + I_q^2 &< I_{max}^2 \\
    V_d^2 + V_q^2 &< V_{max}^2
\end{align*}
\]

Therefore, the principle of field weakening is described in Figure 1a, which presents three zones. The first is the circle that presents the current limitation equation in the first part of the expression (9). The second is the ellipse form designed the voltage limitation in the second part of the equation (9).

The field weakening region is presented by the hachured circle, designed the interconnection between the two last zones. Generally, the current limitation circle is centered in
zero point and her radius depends on the inverter current maximum. It is necessary to indicate, that the limitation voltage contour, can be formed as an ellipse or a circle form: if \( L_d \neq L_q \), or \( L_d = L_q \), respectively. The voltage limitation contour characteristics are characterized essentially by the center point, which depends on the magnet flux and stator inductance values, and the radius value, which depends also on the speed value. Well, if the speed increases, the radius value is reduced. The maximum of current and voltage are usually set by the inverter [5] and [6].

\[
\Delta = 4V_{\text{max}}^2 \left[ R_q^2 + \omega^2 L_d^2 \right] - 4\omega^2 R_d^2 L_q^2 \\
b = 2L_q^2 \omega^2 \lambda_m \\
a = R_s^2 + \omega^2 L_d^2
\]

IV. AHSC ALGORITHM WITH FOC STRATEGY

The FOC strategy is characterized by three PI controllers, the first one is called the PI speed controller, used to generate the quadrature reference stator current after compared the desired and the real speed values. The second one is used to regulate the quadrature stator current for generating the quadrature reference stator voltage. The last one is used to control the direct stator current and for producing the direct reference stator voltage. After obtaining these reference voltages in the rotating dq frame, Clarke transformation is used in order to obtain the corresponding three phases reference stator voltages. Through the PWM bloc the corresponding IGBT switches states are obtained. Then the built stator voltages are feeding the motor. The AHSC-FOC algorithm is placed in this control strategy for generating the corresponding direct reference stator current. The scheme in Figure (2) shows the AHSC-FOC algorithm and the overall FOC PMSM drive scheme as in Figure (3).

To avoid the demagnetization problems, it is necessary to define the direct stator current limit condition, which, can be obtained if the quadrature component is equal to zero. Then, the direct stator current limit is expressed in equation (11).

\[
i_{d,\text{lim}} \bigg| _{i_q=0} = \frac{b - \sqrt{\Delta}}{2a}
\]

Where

\[
\begin{align*}
\Delta &= 4V_{\text{max}}^2 \left[ R_q^2 + \omega^2 L_d^2 \right] - 4\omega^2 R_d^2 L_q^2 \\
b &= 2L_q^2 \omega^2 \lambda_m \\
a &= R_s^2 + \omega^2 L_d^2
\end{align*}
\]

V. AHSC ALGORITHM WITH DTC STRATEGY

The DTC principles can be shown in figure (5), where the errors between the reference and the estimated torque (\( \Delta T_e \)) and flux (\( \Delta \lambda \)) are fixed as the input of two-level hysteresis comparators. Through the switching table, the selection of the corresponding voltage vector is generated. This switching table is explained in the reference [2] and [3]. Generally, in...
the DTC applications, the reference torque is given. However in this application, the desired reference torque is obtained after the appliance of the desired speed goal.

As indicated previously, the stator reference flux value is extremely important if the high speed running mode is applied. Many works about this field in this control strategy are studied as presented in [11] and [12]. However, in the same that Morimoto, the sensitivity to motor parameter variation is the weakness of these methods. Additionally, the chattering phenomena presented in the case of [12], present another disadvantageous. In other hand, the inverter security is not taken account. Therefore, a different high speed control algorithm is applied in this control strategy.

Based on the good performance obtained by the AHSC-FOC algorithm, the AHSC-DTC algorithm is implemented on the DTC technique with a less change. Effectively, a PI controller is added to regulate the direct stator current and to produce the reference direct stator flux. Based on system of equations presented in (12) and characterized the flux vector and the system (13), where \( \theta \) is the angular position, the reference stator flux is obtained in equation (14).

\[
\begin{align*}
\theta_i &= \tan^{-1} \left( \frac{\lambda_{\beta}}{\lambda_{\alpha}} \right) \\
\begin{bmatrix}
\lambda_{\alpha} \\
\lambda_{\beta}
\end{bmatrix} &= \begin{bmatrix}
\cos(\theta) & -\sin(\theta) \\
\sin(\theta) & \cos(\theta)
\end{bmatrix} \begin{bmatrix}
\lambda_{d} \\
\lambda_{q}
\end{bmatrix} \\
\lambda^{*}_{q} &= \sqrt{\lambda^{*}_{\alpha}^2 + \lambda^{*}_{\beta}^2}
\end{align*}
\]

The AHSC-DTC is then illustrated in figure (4).

In order to show the performance of the proposed AHSC algorithm, a hardly test in a wide speed region is applied. Effectively, the given variable reference speed is started from 0 rpm to the rated values. Then, from the rated one to exceed it up to 4000 rpm. In this application, the load torque applied on the motor is similar to the electric vehicle approach. Well, the load torque decreases if the desired speed exceeds the rated one.

In figure 6 and 7, the present results are illustrated in the FOC case. These figures show respectively the evolution of the speed and the electromagnet torque in the case of the 100% of the rated speed and in the case of 160% of the rated one. The corresponding direct stator current, generated from the AHSC-FOC is shown in the same figure. Figure.7 makes clear the field weakening principle. It is important to indicate that the maximum speed can be more increased but only if we decrease more the load torque and unsure the maximum current condition.

The overall control scheme illustrates the DTC strategy in the high speed mode can be then presented in figure (5).
The corresponding FOC Speed, torque and direct stator current results in 100% and 160% of the rated speed.

The corresponding FOC Field weakening comportment in 100% and 160% of the rated speed.

The DTC case is also applied and the AHSC-DTC is implemented as presented in the figure. The corresponding results in figure 8 and 9 show respectively, the speed, torque, direct stator current and the flux components. The satisfaction of the proposed AHSC-DTC algorithm is verified under the same condition as the FOC case.

An adaptive high speed control algorithm has been presented. MRAS estimator and the Morimoto constraints are used to build the proposed high speed control algorithm. This proposed algorithm is formulated and applied in the two conventional control strategies as the FOC and the DTC. The effectiveness of the proposed high speed control algorithm is proven over simulation results where a wide speed region equal to 160% of the rated speed is highlighted. The drive system has operated satisfactorily in a wide speed range suitable for electrical vehicle applications.

REFERENCES


