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# Disturbance Observer and Adaptive Robust Control for PMSM Drive using MRAS-based Parameters Estimation

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**Abstract**— This paper proposes an adaptive robust control strategy for permanent magnet synchronous machine based on speed and currents disturbance observation. The suggested approach uses the model reference adaptive system to estimate the motor's parameters that are needed to tune the controllers. However, a significant challenge arises due to the variation of motor parameters which impact the speed and current control when the temperature increases. The proposed robust control technique combines cascaded controllers, resistance, inductance and flux linkage estimation to ensure accurate regulation of stator currents and rotor speed. Including an adaptive system for parameters variations, the proposed model helps to compensate the control errors and to maintain the system performance. Simulation results demonstrate the effectiveness of the proposed adaptive robust control strategy.

**Keywords**— permanent magnet synchronous motor, adaptive control, robust control, disturbance, observer, model reference adaptive system.

## I. INTRODUCTION

Recently, the use of Permanent Magnet Synchronous Machines (PMSM) has surged in modern applications, driven by their many advantages including high efficiency, superior torque density, high mass power density and precise control capabilities [1]. These machines have become increasingly favored in the industry for their ability to deliver high performance operating condition while maintaining energy efficiency and accuracy in operation. The Field Oriented Control (FOC) methodology had significant attention in previous research works owing to its straightforward implementation and high dependability. In FOC, a closed loop control system is employed, consisting of cascaded speed and currents loops. In this setup the outer loop is, in charge of maintaining a speed while the inner loop controls the  $q$  and  $d$  axis currents to produce the required voltage references [2]. The drawbacks of FOC include its sensitivity to motor parameters, meaning that disturbances in quantities such as resistance and flux in high-temperature applications [3], [4] can impact both control robustness and transient behavior, potentially leading to undesirable oscillations. A variety of nonlinear control methods have been proposed to enhance the

robustness of the speed control of PMSMs. These methods include sliding mode control [5], predictive control, backstepping control,  $\mu$ -synthesis control,  $H^\infty$  control, Active Disturbance Rejection Control (ADRC) and Disturbance Observer Based Control (DOBC) [6], [7], [8].

For the robust control of stator currents of PMSM, there are several approaches have been developed such as Internal Model Control (IMC), Model-Free Predictive Current Control (MFPCC) or Adaptive Robust Control (ARC) [7], [9],[10]. The first two methods consist at estimating disturbances resulting from variations in system parameters and compensating them in the control while ARC is based on adaptive estimation of resistance, inductance, and permanent magnet flux, which can be then used in the control.

With the importance of accurate estimation of the parameters in adaptive control for PMSM, various numerical methods are employed like Recursive Least Squares (RLS), Extended Kalman Filter (EKF), or projection-based parameter adaptation [11]. Other analogical approaches such as Model Reference Adaptive System (MRAS) are based on *Popov* and *Lyapunov* lemma [12], [13], [14].

In [7], A DOBC with ARC is proposed using the projection method to estimate the parameters. However, this estimation method is not suitable with high parameters variation like in high temperature applications. Therefore, this paper proposes the MRAS estimation method that is more adapted for such applications. The DOBC is employed for the speed regulation and the concepts of ARC for the motor's stator currents.

This paper is summarized as follows: Section II describes the modeling of PMSM in the  $d$ - $q$  axis. An overview of the DOB rotor speed control model is provided in Section III. Section IV is dedicated to the MRAS-based motor parameter estimation. The ARC using MRAS is developed in Section V. Simulation results with MATLAB/Simulink are presented for validation model in Section VI, followed by the conclusion in the last section.

## II. PMSM'S MODEL:

For the study of the robustness of proposed adaptive control strategy the whole system including motor, controllers and estimator system has been developed. The permanent magnet synchronous machines model in the  $dq$  axis is given by following equations [1]:

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \quad (1)$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \lambda_m \quad (2)$$

$$T_e = \frac{3}{2} p [\lambda_m i_q + (L_d - L_q) i_d i_q] = \frac{3}{2} p \lambda_m i_q \quad (3)$$

$$T_e - T_l = J \frac{d\Omega}{dt} + f_c \Omega \quad (4)$$

$$\omega = n_p \Omega \quad (5)$$

The motor voltages and currents in the  $dq$  reference frame are represented by  $u_d, u_q$ , and  $i_d, i_q$  respectively.  $\lambda_m$  is the permanent magnet flux.  $R_s, L_d$  and  $L_q$  are respectively the stator resistance,  $d$  and  $q$  inductance ( $L_d = L_q = L$  in our case).  $T_e$  stands for the electromagnetic torque,  $\Omega$  and  $\omega$  are the rotor and electrical velocity,  $n_p$  represents the number of pole pairs,  $T_l$  is the load torque,  $J$  is the rotor's inertia, and  $f_c$  is the friction coefficient.

## III. SPEED REGULATION USING DISTURBANCE OBSERVER BASED SPEED CONTROLLER

The Disturbance observer is used to estimate plant uncertainties and external disturbances, it was defined the first time in 1983 [8]. The disturbance is presented in the nonlinear state space representation as follows [6]:

$$\frac{dx}{dt} = f(x) + g_1(x)u + g_2(x)D \quad (6)$$

where  $x$  is the state vector,  $u$  is the control input,  $D$  represents the total disturbance in the system,  $f(x), g_1(x)$  and  $g_2(x)$  are functions of the state  $x$ . In most cases, it is difficult to measure the disturbance  $D$  directly, so it will be estimated.

According to [6], the disturbance  $\hat{D}$  can be estimated as follows:

$$\begin{cases} \hat{D} = z + p(x) \\ \frac{d}{dt} z = -l(x)[g_2(x)z + g_2(x)p(x) + f(x) + g_1(x)u] \end{cases} \quad (7)$$

where  $z$  is an internal vector,  $p(x)$  is function of  $x$  to be tuned and  $l(x) = \partial p(x)/\partial x$  is the observer gain. Let consider  $e_D = D - \hat{D}$  the disturbance error estimation, if we suppose that  $dD/dt \approx 0$ , we can easily obtain:

$$\frac{d}{dt} e_D + \frac{\partial p(x)}{\partial x} g_2(x) e_D = 0 \quad (8)$$

So, to ensure the stability of the observer, we can take:

$$\frac{\partial p(x)}{\partial x} = \frac{l}{g_2(x)}, l > 0 \quad (9)$$

then:

$$\frac{d}{dt} e_D + l e_D = 0 \quad (10)$$

and therefore  $e_D = m e^{-lt} \rightarrow 0$ . So  $e_D$  is null at steady state ( $t \rightarrow \infty$ ).

In the PMSM, the mechanical rotor speed equation can be written as [7]:

$$J \frac{d\Omega}{dt} = T_e - T_l - f_c \Omega + \Delta_p \quad (11)$$

where  $\Delta_p$  is the parametric uncertainties.

The speed disturbance  $D_w$ , which include of all disturbance terms in rotor speed control, can be expressed:

$$D_w = \frac{1}{J} (f_c \Omega + T_l - \Delta_p) \quad (12)$$

Substituting (12) and (3) in (11):

$$\frac{d\Omega}{dt} = \frac{3 n_p \lambda_m}{2 J} i_q - D_w = k_t i_q - D_w \quad (13)$$

where  $k_t = 1.5 n_p \lambda_m / J$  is the torque constant.

Based on (7) and (13),  $x$  in our system is the rotor velocity  $\Omega$  and  $g_2(x) = -1$ , so we can consider  $p(\Omega) = -l\Omega$ ,  $\hat{D}_w$  can be estimated as follows:

$$\begin{cases} \hat{D}_w = z - l\Omega \\ \frac{dz}{dt} = l(k_t i_q - z + l\Omega) = l(k_t i_q - \hat{D}_w) \end{cases} \quad (14)$$

where  $\hat{D}_w$  is the estimated value of  $D_w$ , and  $l$  is the observer gain. We assume that the closed loop transfer function between the reference speed and the measured speed is a first-order function with time constant  $\tau_w$ , so:

$$\Omega^*(s) = \Omega(s)(1 + \tau_w s) \quad (15)$$

In the cascade control of PMSM, the reference value  $i_q^*$  is the output of the speed controller, and can be replaced  $i_q$  in (13) and (15).

Substituting the time domain of (12) ( $\Omega + \tau_w d\Omega/dt = \Omega^*$ ) in (13) and using  $\hat{D}_w$  instead of  $D_w$ ,  $i_q^*$  can be written as:

$$i_q^* = \frac{1}{k_t} \left( \frac{1}{\tau_w} e_w + \hat{D}_w \right) \quad (16)$$

where  $e_w = \Omega^* - \Omega$ , is the speed control error.

#### IV. MODEL REFERENCE ADAPTIVE SYSTEM ESTIMATOR

In this part, the MRAS technique employed for estimating the PMSM parameters ( $R_s, L$  and  $\lambda_m$ ) is described [12]. These parameters will be used in the next section for currents control.

The state space equation of the motor can be written as:

$$\frac{di}{dt} = Ai + Bu + C \quad (17)$$

where  $i = [i_d \ i_q]^T$ ,  $u = [u_d \ u_q]^T$ ,

$$A = \begin{bmatrix} -\frac{R_s}{L} & \omega \\ -\omega & -\frac{R_s}{L} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}, C = \begin{bmatrix} 0 & \frac{\lambda_m}{L} \\ -\omega & \frac{\lambda_m}{L} \end{bmatrix},$$

and for modeling it is considered that  $L_d = L_q = L$ .

The adjustable parameter model of the estimated currents  $\hat{i}$  is:

$$\frac{d\hat{i}}{dt} = \hat{A}\hat{i} + \hat{B}u + \hat{C} + G(\hat{i} - i) \quad (18)$$

$$\text{where } \hat{A} = \begin{bmatrix} -\frac{\hat{R}_s}{\hat{L}} & \omega \\ -\omega & -\frac{\hat{R}_s}{\hat{L}} \end{bmatrix}, \hat{B} = \begin{bmatrix} \frac{1}{\hat{L}} & 0 \\ 0 & \frac{1}{\hat{L}} \end{bmatrix}, \hat{C} = \begin{bmatrix} 0 & \frac{\hat{\lambda}_m}{\hat{L}} \\ -\omega & \frac{\hat{\lambda}_m}{\hat{L}} \end{bmatrix},$$

$$G = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix}, K_1, K_2 > 0.$$

Subtracting (18) from (17):

$$\frac{d\hat{e}}{dt} = (A + G)\hat{e} + (A - \hat{A})\hat{i} + (B - \hat{B})u + (C - \hat{C}) \quad (19)$$

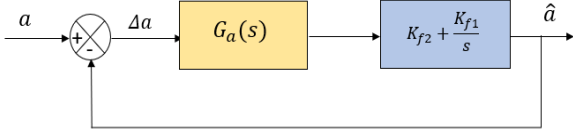


Fig. 1. Bloc diagram of the closed loop transfer function of MRAS based estimation

where  $\hat{e} = (i - \hat{i})$  is the error estimation vector.

Considering  $w = (A - \hat{A})\hat{i} + (B - \hat{B})u + (C - \hat{C})$ , (19) can be written as:

$$\frac{d\hat{e}}{dt} = (A + G)\hat{e} + w. \quad (20)$$

The above system consists of two parts: one linear forward component ( $A + G$ ) and nonlinear feedback component ( $w$ ).

To ensure the stability of the system, both of these conditions must be met:

1. The transfer function matrix of the linear forward block must be strictly positive real.
2. The nonlinear feedback term satisfies Popov integral inequation:

$$\int_0^t w^T \hat{e} d\tau \geq -\gamma_0^2, \gamma_0 > 0.$$

The first condition can be established if [13]:

$$P(A + G) + (A + G)^T P = -Q$$

where  $P$  is a symmetrical positive matrix and  $Q$  is symmetrical positive semidefinite (i.e. its eigenvalues are positive or zero). Let's consider:

$$P = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$P(A + G) + (A + G)^T P = -2 \begin{bmatrix} \frac{R_s}{L} - K_1 & 0 \\ 0 & \frac{R_s}{L} - K_2 \end{bmatrix} = -Q$$

To ensure that  $Q$  is symmetrical positive semidefinite, it is required that:

$$\begin{cases} K_1 \leq \frac{R_s}{L} \\ K_2 \leq \frac{R_s}{L} \end{cases} \quad (21)$$

By applying condition 2, we can easily derive the next equation (22) for the estimated parameters [12] where  $\hat{R}_s(0), \hat{L}(0), \hat{\lambda}_m(0)$  are initial values,  $K_{f,g,h,2}, K_{f,g,h,1}$  are the proportional and integral gains of PI controller,  $\hat{e}_d = \hat{i}_d - i_d$ , and  $\hat{e}_q = \hat{i}_q - i_q$ .

$$\begin{cases} \frac{\hat{R}_s}{\hat{L}} = \frac{\hat{R}_s(0)}{\hat{L}(0)} - (K_{f2} + \frac{K_{f1}}{s})(\hat{i}_d \hat{e}_d + \hat{i}_q \hat{e}_q) \\ \frac{1}{\hat{L}} = \frac{1}{\hat{L}(0)} + (K_{g2} + \frac{K_{g1}}{s})(u_d \hat{e}_d + u_q \hat{e}_q) \\ \frac{\hat{\lambda}_m}{\hat{L}} = \frac{\hat{\lambda}_m(0)}{\hat{L}(0)} - (K_{h2} + \frac{K_{h1}}{s})(\omega \hat{e}_q) \end{cases} \quad (22)$$

Let's consider the notation  $a = R_s/L$ ,  $b = 1/L$  and  $c = \lambda_m/L$ ; based on (19) and (22), the block schematic of the closed-loop transfer function between the estimated  $\hat{a}$  and real  $a$  of the machine can be made as presented in Fig.1 (the same for  $b$  and  $c$ ). where the  $G_{abc}(s)$  expressions can be written:

$$\begin{cases} G_a(s) = \frac{(s + a - K_2)\hat{i}_d^2 + (s + a - K_1)\hat{i}_q^2}{(s + a - K_2)(s + a - K_1) + \omega^2} \\ G_b(s) = \frac{(s + a - K_2)u_d^2 + (s + a - K_1)u_q^2}{(s + a - K_2)(s + a - K_1) + \omega^2} \\ G_c(s) = \frac{(s + a - K_1)\omega^2}{(s + a - K_2)(s + a - K_1) + \omega^2} \end{cases} \quad (23)$$

After selecting the values of  $K_{f,g,h,1}$  and  $K_{f,g,h,2}$ , by plotting the zeros and poles of the system presented in Fig.1, it is possible to verify its stability as presented in [14].

#### V. ADAPTIVE ROBUST CONTROL PMSM'S CURRENTS

Equations (1) and (2) of the PMSM can be written as following:

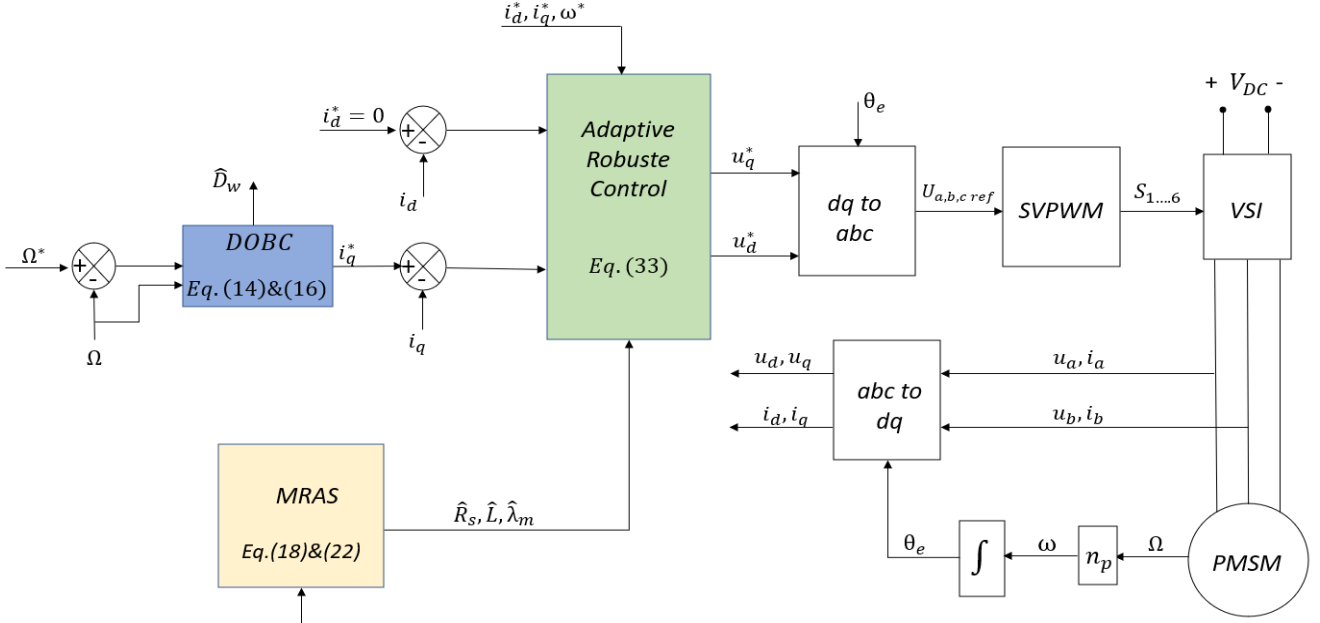


Fig. 2. Bloc diagram of the complete control of velocity and currents with MRAS estimation

$$\begin{cases} L_q \frac{di_q}{dt} = \varphi_q^T \theta_q + u_q \\ L_d \frac{di_d}{dt} = \varphi_d^T \theta_d + u_d \end{cases} \quad (24)$$

where  $\varphi_q = [-i_q \quad -\omega i_d \quad -\omega]^T$ ,  $\varphi_d = [-i_d \quad \omega i_q]^T$ ,

$\theta_q = [R_s \quad L \quad \lambda_m]^T$ ,  $\theta_d = [R_s \quad L]$ .

With variations in  $R_s$ ,  $L$  and  $\lambda_m$ , the electrical part of the motor can be modeled as follows [7]:

$$\alpha \frac{dX}{dt} = \varphi^T \theta + u + \Delta \quad (25)$$

where  $X = [x_d \quad x_q]^T = [i_d \quad i_q]^T$  is the state variable,  $\alpha$  is the time derivative coefficient of  $X$ ,  $\Delta$  represents the parameter perturbations.

$$\varphi^T = \begin{bmatrix} \varphi_d^T & 0 \\ 0 & \varphi_q^T \end{bmatrix} \text{ and } \theta = [\theta_d \quad \theta_q]^T.$$

The adaptive robust control of the currents consists of two parts [9]:

1. An adaptive compensation  $u_a$  that does not consider any perturbations ( $\Delta = 0$ ).
2. A robust regulation  $u_f$  that takes perturbations into account ( $\Delta \neq 0$ )

According to [7], the adaptive regulation function can be defined as follows:

$$\begin{aligned} u_a &= \alpha \frac{dX^*}{dt} - \varphi^T \hat{\theta} - k(X - X^*) \\ &= \alpha \frac{dX^*}{dt} - \varphi^T \hat{\theta} - ke \end{aligned} \quad (26)$$

where  $X^*$  is the reference of  $x$ ,  $\hat{\theta}$  represents the estimated parameters and  $e = (X - X^*)$  is the error control.

Substituting (26) in (25):

$$\alpha \frac{de}{dt} + ke = -\varphi^T (\hat{\theta} - \theta) = -\varphi^T \Delta_\theta \quad (27)$$

where  $\Delta_\theta$  is the parameters estimation error. Differently from the ideal ARC, which uses the projection mapping law to estimate parameters [10], we will implement the MRAS developed in the previous section and verify the stability of the new currents law control.

Let's consider  $V$  a Lyapunov function containing the regulation error  $e$  and the estimation error  $\hat{e}$ :

$$V = V(e) + V(\hat{e}) = \frac{1}{2} \alpha e^2 + \frac{1}{2} \hat{e}^2 \geq 0 \quad (28)$$

$$\frac{dV}{dt} = \frac{dV(e)}{dt} + \frac{dV(\hat{e})}{dt} = \quad (29)$$

$$= e(-ke - \varphi^T \Delta_\theta) + \hat{e}[(A + G)\hat{e} + w]$$

The both conditions in section IV are satisfied, then  $dV(\hat{e})/dt \leq 0$ , and without parameter perturbations,  $\Delta_\theta$  converges to 0 with MRAS and  $e$  converges to 0 in (24). So,  $dV/dt$  can be written as:

$$\frac{dV}{dt} \simeq -ke^2 + \hat{e}[(A + G)\hat{e} + w] \leq -ke^2 \leq 0. \quad (30)$$

then, the stability of the proposed adaptive robust control with MRAS-based parameter estimation is verified.

For the robust feedback regulation, we will consider the disturbances of the system. So, (27) becomes:

$$\alpha \frac{de}{dt} + ke = u_f - (\varphi^T \Delta_\theta + \Delta) \quad (31)$$

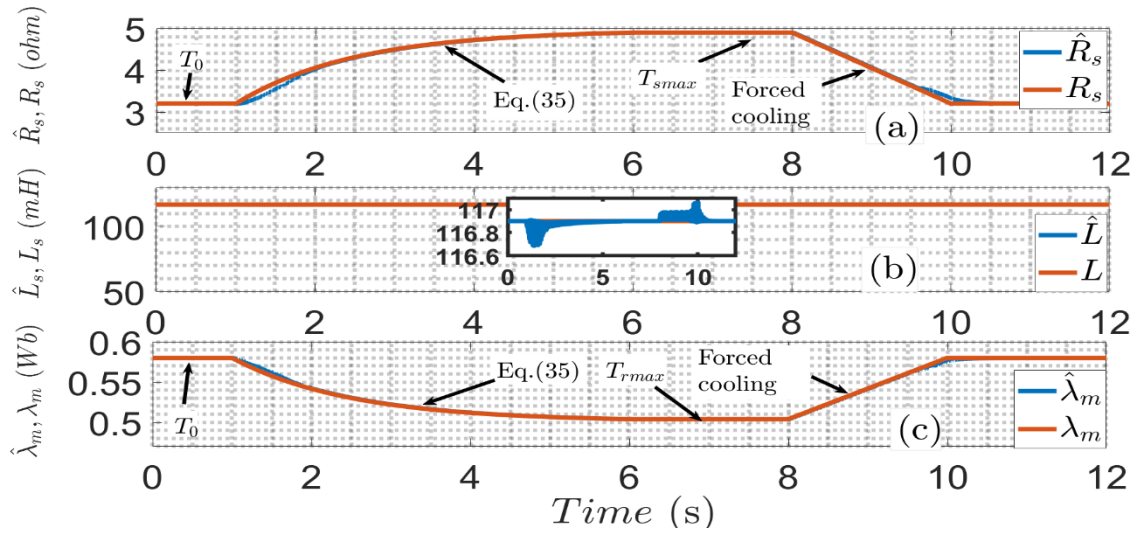


Fig. 3. Estimation and actual values of: (a) stator resistance, (b) stator inductance and (c) permanent magnet flux.

Let's note  $h = |\varphi^T| |\theta_{max} - \theta_{min}| + |\Delta|$ , where  $\theta_{max}$  and  $\theta_{min}$  are the maximum and minimum values of  $\theta$  respectively.

The robust feedback can be written considering [9]:

$$u_f = -h \times \text{sgn}(e) \quad (32)$$

In practical applications,  $h \times \text{sgn}(e)$  is often replaced by  $1/(4\varepsilon)h^2e$ , where  $\varepsilon$  is a small number.

The complete control law of the  $i_q$  current:

$$u_q^* = u_{aq} + u_{fq} = \alpha \frac{dx_q^*}{dt} - \varphi_q^T \hat{\theta}_q - ke_q - \frac{1}{4\varepsilon} h_q^2 e_q \quad (33)$$

Table 1. Parameters values of the simulated PMSM

$R_s (\Omega)$	$L(H)$	$\lambda_m(Wb)$	$J(kg.m^2)$	$f_c(N.m.s.rad^{-1})$
3.2	0.1169	0.58	0.002	0.0075

where  $\hat{\theta}_q$  comes from (22).

Let's consider  $V_q = 1/2\alpha e_q^2 \geq 0$  a Lyapunov function. To demonstrate the stability of the proposed control law, we should have  $dV_q/dt \leq 0$ .

$$\begin{aligned} \frac{dV_q}{dt} &= e_q(-ke_q + u_{fq} - \varphi_q^T \Delta_\theta + \Delta_q) \\ &\leq -ke_q^2 + |e_q|(-h_q + |\varphi_q^T \Delta_\theta + \Delta_q|) \\ &\leq -ke_q^2 \leq 0 \end{aligned} \quad (34)$$

The same control law is applied to  $i_d$ . To reduce the impacts of measurement noises in the system,  $i_d$ ,  $i_q$  and  $\omega$  have been replaced by their references in  $\varphi$  and  $h$  [7]. The bloc diagram of the whole system is illustrated in Fig.2.

## VI. SIMULATION RESULTS

In this section, the results obtained by simulation with proposed ARC and MRAS method are compared with those

obtained by FOC. For study it is considered a PMSM with parameters detailed in Table 1. Firstly, it is assumed a rotor speed  $\Omega = 1500 \text{ rpm}$ . Between 0 and 1 second, the motor will operate under no-load conditions and without parameters perturbation, after that, a 16 N.m. load torque is applied. We will assume that the inductances are independent of temperature, while the resistance and permanent magnet flux change based on the temperature as follows [3], [4]:

$$\begin{cases} R_s = R_{s0}[1 + \gamma(T_s - T_0)] \\ \lambda_m = \lambda_{m0}[1 + \beta(T_r - T_0)] \end{cases} \quad (35)$$

where  $R_{s0}$  and  $\lambda_{m0}$  are the initial value of  $R_s$  and  $\lambda_m$  respectively, ( $\gamma > 0$ ) and ( $\beta < 0$ ) are thermal coefficients that depend on the materials,  $T_0 = 20^\circ\text{C}$ ,  $T_s$  and  $T_r$  are the ambient, actual stator and rotor temperature respectively.

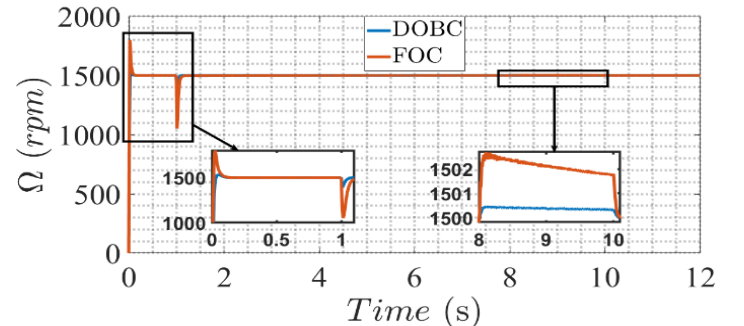


Fig. 4. Simulation of controlled rotor speed of PMSM

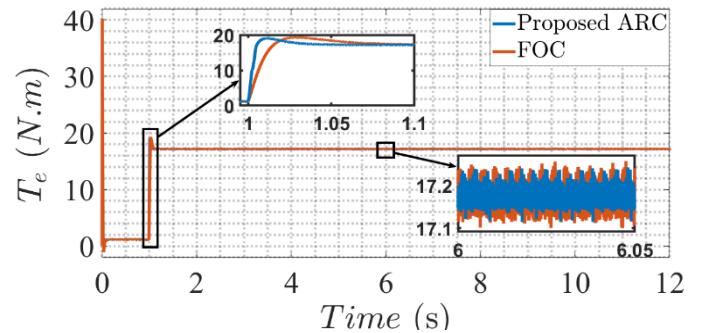


Fig. 5. Simulation results of electromagnetic torque

The following assumptions have been considered:

1. There are no variations in parameters in the initial phase when the motor operates without load.
2. Resistance and flux follow (35) when a load is applied ( $\gamma = 0.00393 \%/^{\circ}\text{C}$  and  $\beta = -0.0008 \%/^{\circ}\text{C}$ ) when  $T_s$  and  $T_r$  are first order system over time [15].
3. They stabilize in steady state as the temperature becomes stable ( $T_{s\max} = 140^{\circ}\text{C}$  and  $T_{r\max} = 170^{\circ}\text{C}$ ).
4. The stator and rotor temperature decrease to the ambient temperature as the machine is cooled (forced cooling) and the parameters return to their initial value.
5. To reduce the simulation time, we will decrease the durations specified in assumptions 2, 3, and 4 as

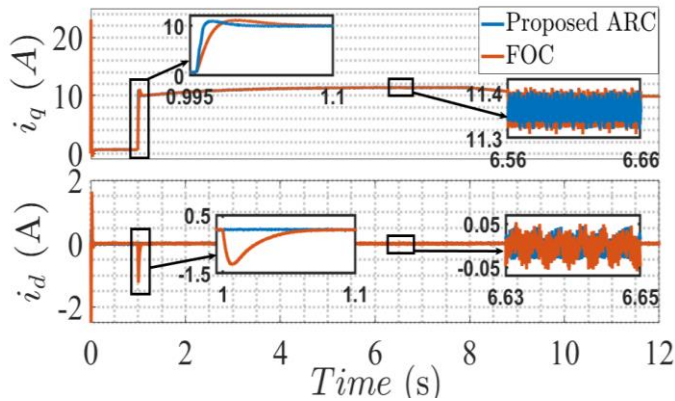


Fig. 6. Simulation results of  $dq$  currents

presented in Fig.3.

The resistance, inductance and permanent magnet flux using the MRAS (Fig. 3), and these estimations are used in ARC (Fig.2).

Fig. 4 illustrates the measured rotor speed in both the proposed ARC method and the FOC. We initially set the speed to achieve the same response time under no-load conditions in both methods, but when applying a load, it is noticed that the response time of the DOBC is better than that of the FOC, with relatively lower overshoot and error (between 8 and 10 seconds when the machine cools).

Fig.5 shows the electromagnetic torque generated by the motor, we can note in the ARC mode a slight reduction in the response time and an observed decrease in oscillations magnitude.

The  $dq$  axes currents are shown in Fig.6. We can note better stability for  $i_d$  and  $i_q$  regulated by ARC in transient case created by load variation and less oscillation in steady-state mode. This method allows to adjust the machine parameters uses in the control loop to improve the control performances.

## VII. CONCLUSION

An adaptive robust current control using a model reference adaptive system for parameters estimation has been detailed and simulated in this paper. The results obtained are compared to those simulated by the classically Field Oriented Control methodology to study the influence of the

parameters variation in speed and current regulation in the presence of motor temperature variation. The results presented in the paper demonstrate that current regulation becomes more adaptive and robust by using the estimated parameters as references, particularly when the motor operates in transient and high-temperature conditions. The speed adjustment was achieved through disturbance observer-based control, which proves to be more robust against parameter variations compared to the conventional PI controller. MATLAB/Simulink was used to validate the estimation and control outcomes.

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