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► **To cite this version:**

Riyad Jbayli, Younes Azzoug, Romain Cousseau, Rémus Pusca, Raphaël Romary. Robust control of a high-temperature synchronous machine with anodized aluminum coils. Symposium on Advanced Technologies in Electrical Systems - SATES 2025, Université de Lorraine, Apr 2025, Nancy, France. ⟨hal-05061161⟩

HAL Id: hal-05061161

<https://hal.science/hal-05061161v1>

Submitted on 9 May 2025

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Adaptive Robust Control for Synchronous Machines with Anodized Aluminum Windings Designed for High Temperature Operation

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This work has been achieved within the framework of EE4.0 project (Energie Electrique 4.0). EE4.0 is co-financed by European Union with the financial support of the European Regional Development Fund (ERDF), French State and the French Region of Hauts-de-France.

Objective – This paper presents a robust control strategy for wound rotor synchronous machine with anodized aluminum windings designed to operate at temperatures up to 300°C. At these high temperatures, resistance and magnetic flux can fluctuate significantly, challenging conventional control methods that depend on fixed machine parameters. This highlights the importance of a robust control strategy to effectively handle these variations.

Findings – This control law has demonstrated its effectiveness in regulating machine speed and currents by enhancing the dynamics and reducing oscillations during steady-state operation. It also shows more adaptability compared to conventional control methods, such as Field-Oriented Control.

Originality – Making a robust control for a high-temperature wound rotor aluminum coil machine by taking into account the losses and real-time parameters variations and estimating them. This problem is not a very present topic in the literature.

Keywords – Synchronous machine, Disturbance Observer, MRAS, Adaptive Robust Control, Anodized aluminum windings, High temperature.

1. Introduction

Advancements in industrial automation, transportation, and renewable energy have created a need for electrical machines that provide higher efficiency, reliability, and better dynamic performance. Among these, **Wound Rotor Synchronous Machines (WRSM)** have gained significant attention due to their high torque density, compact structure, and precise control capabilities. A comparison between a WRSM with aluminum coils and a **Permanent Magnet Synchronous Machine (PMSM)** was made in [1], showing that the first can withstand much higher temperatures in the rotor. Aluminum is a very interesting alternative to copper because it is cheaper, lighter, and allows good thermal conductivity. The use of aluminum wire will allow a 50% reduction in the total mass of the stator coils, even with a larger cross-section [2]. Furthermore, studies have been conducted to compare aluminum with copper in the winding of electric machines, and aluminum has proven its effectiveness in high-frequency and high-speed applications [3].

Since anodized aluminum coils can operate at temperatures up to 300°C, this can have negative effects on the control of these machines, especially with conventional control methods such **Field Oriented Control (FOC)** that depend on the machine parameters [4]. At these high temperatures, the resistance of the coils increases significantly, and the rotor flux decreases due to the reduction of the excitation current under a constant voltage, caused by the increasing of the rotor resistance. In [5], authors present the negative effects of parameter variations of the motor on the transfer function and the PI controller.

To address these challenges, researchers have explored a variety of nonlinear control techniques aiming at improving the robustness of synchronous machine control under varying conditions. Among these, sliding mode control [6], predictive control, and backstepping control [7] have proven effective in compensating for parameter variations and disturbances. These methods provide enhanced performance by adjusting control parameters in real time, thus improving the system's ability to withstand external disturbances and internal uncertainties. Additionally, advanced methods like μ -synthesis control and H_∞ control are used to manage uncertainties and enhance system stability in the presence of large disturbances. Finally, the **Disturbance Observer-Based Control (DOBC)** [8], [9], [10] estimates the

disturbances caused by variations in the parameters on the rotor's mechanical movement and compensates for them in the control.

However, even with these advanced methods, synchronous machines still have limitations when working in very high temperature conditions, where motor parameters change sharply. In these situations, traditional control methods may have trouble keeping the performance at its best, especially for controlling the stator current. To overcome this limitation, more advanced adaptive control methods have been developed. Internal Model Control (IMC), Model-Free Predictive Current Control (MFPC), and Adaptive Robust Control (ARC) [10], [11] are examples of techniques that focus on estimating and compensating for disturbances caused by parameter changes. While IMC and MFPC focus on estimating and compensating of these disturbances in a model-based manner, ARC offers a more flexible solution by continuously adapting the changes in motor parameters, such as resistance, inductance, and rotor flux.

Accurate parameter estimation is crucial to the success of adaptive control in synchronous machines, especially in high-temperature applications where parameter variations are more pronounced. Various numerical techniques, such as Recursive Least Squares (RLS) [12], Extended Kalman Filter (EKF) [13], or projection-based adaptation method [14], have been widely used to estimate motor parameters in real-time. These methods enable the controller to adapt the variations of the parameters dynamically, ensuring optimal performance even in fluctuating conditions. Furthermore, Model Reference Adaptive Systems (MRAS) [15], [16], which apply Popov and Lyapunov's lemmas for stability, have been proposed as alternative approaches for parameter adaptation, offering improved robustness in uncertain environments.

In [17], an improved Adaptive Robust Control for PMSM currents employing MRAS was proposed for parameter estimation instead of the projection method. In our work, we will apply this approach to a synchronous machine with anodized aluminum coils in stator and rotor and the results are compared with those obtained by Field Oriented Control. This paper is organized as follows: Section 2 covers the equations of the WRSM. Sections 3 and 4 discuss the DOBC proposed for speed control and MRAS for estimating the machine parameters with their numerical implementation. The ARC method used for current control is explained in Section 5. Simulation results are shown in Sections 6. Finally, the paper ends with a conclusion in the last section.

2. Model of Wound Rotor Synchronous Machine

The model of the wound rotor synchronous machine in the dq axis used in simulation is described by the following equations:

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

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

$$T_e = \frac{3}{2} p L_m i_r i_q \quad (3)$$

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

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

$$V_r = R_r i_r + L_r \frac{di_r}{dt} \quad (6)$$

In the dq reference, the motor voltages and currents are denoted as u_d, u_q and i_d, i_q respectively. The parameter L_m represents the mutual inductance between the rotor excitation winding and the stator winding, both aligned with the d axis of the rotor. The stator resistance, the d and q axis inductances, are given by R_s, L_d , and L_q respectively (we will consider $L_d = L_q = L$). T_e is the electromagnetic torque, while Ω and ω correspond to the rotor and electrical speeds. n_p is the number of pole pairs. Additionally, T_l represents the load torque, J denotes the rotor's moment of inertia, and f_c is the coefficient of friction. Equation (6) describes the DC excitation of the rotor, where V_r is the constant DC supply voltage, i_r is the rotor current, while R_r and L_r represent the rotor resistance and inductance respectively. Since the voltage remains steady, we assume $L_r di_r/dt \approx 0$ and neglect the inductive term.

For motor regulation we will use the cascade control method. First, the speed is controlled to generate the reference current i_q^* . The reference i_d^* is set to zero to ensure Maximum Torque Per Ampere (MTPA). Next, the currents are controlled to generate the voltages reference u_d^* and u_q^* . After a park transformation, these voltages are applied to the motor through a PWM and an inverter, ensuring the desired speed is achieved.

3. Disturbance Observer for Rotor Speed Control

The Disturbance Observer is used to estimate uncertainties in the system [17]. In the nonlinear state-space representation, the disturbance is expressed as follows [8]:

$$\frac{dx}{dt} = f(x) + g_1(x)u + g_2(x)D \quad (7)$$

Here, x denotes the state vector, u represents the control input, and D accounts for the total disturbance affecting the system. The functions $f(x)$, $g_1(x)$ and $g_2(x)$ depend on the state x . Since measuring the disturbance D directly is often challenging, it is instead estimated. The disturbance \hat{D} can be approximated using the following equation:

$$\begin{cases} \hat{D} = z + p(x) \\ \frac{dz}{dt} = -l(x)[g_2(x)z + g_2(x)p(x) + f(x) + g_1(x)u] \end{cases} \quad (8)$$

In this context, z is an internal vector, $p(x)$ is a function of x , and $l(x) = \partial p(x)/\partial x$ is the gain of the observer. Assuming that $e_D = D - \hat{D}$, to ensure the convergence of this system, meaning that e_D tends to zero, we can apply the following equation:

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

The disturbance observer can be applied to control the speed of the WRSM. Equation (4) can be written with the parametric uncertainties Δ_p in the system:

$$J \frac{d\Omega}{dt} = T_e - T_l - f_c \Omega + \Delta_p \quad (10)$$

The disturbance of the system is considered as $D_w = 1/J(f_c \Omega + T_l - \Delta_p)$ to obtain the following equation for the speed:

$$\frac{d\Omega}{dt} = \frac{3 n_p L_m i_r}{2 J} i_q - D_w = k_t i_q - D_w \quad (11)$$

where $k_t = 1.5 n_p L_m i_r / J$ is the torque constant.

Based on equations (8) and (11), we can estimate \hat{D}_w as follows:

$$\begin{cases} \hat{D}_w = z - \eta \Omega \\ \frac{dz}{dt} = \eta(k_t i_q - z + \eta \Omega) = \eta(k_t i_q - \hat{D}_w) \end{cases} \quad (12)$$

If we consider that the closed-loop transfer function between the reference speed Ω^* and the measured speed Ω , is considered as a first-order function with a time constant τ_w ($\Omega^*(s) = \Omega(s)(1 + \tau_w s)$), then the output of the speed controller i_q^* can be defined as following:

$$i_q^* = \frac{1}{k_t} \left(\frac{1}{\tau_w} e_w + \hat{D}_w \right) \quad (13)$$

where $e_w = \Omega^* - \Omega$, is the speed control error. Figure 2 shows the implementation of the speed regulation diagram based on the Disturbance Observer-Based Control (DOBC) algorithm.

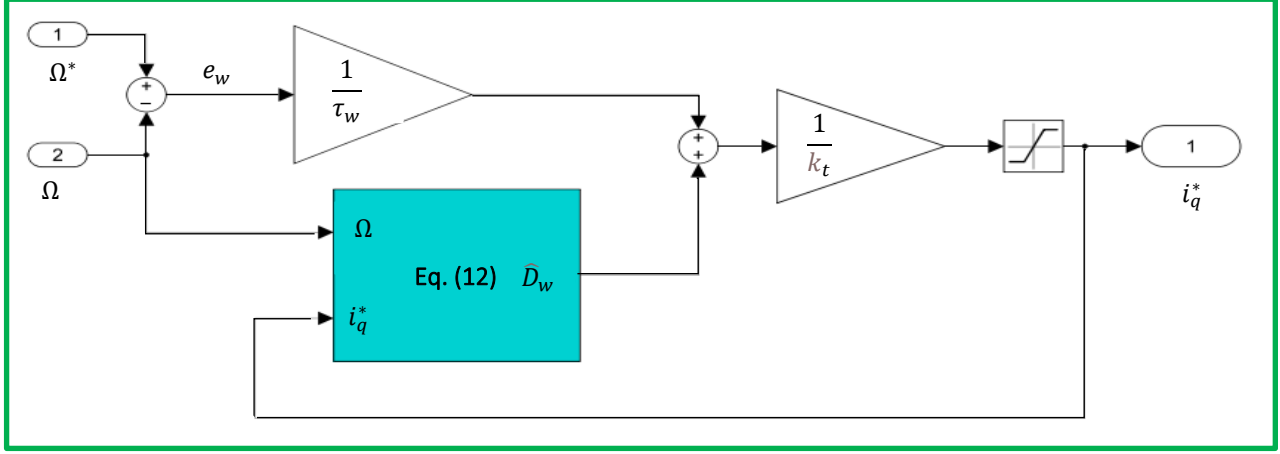


Figure 1: The block diagram of the speed regulation using Disturbance Observer-Based Control algorithm

4. Model Reference Adaptive System (MRAS) for Parameters Estimation

This section focuses on the use of the MRAS technique for estimating the resistance R_s , inductance L , and rotor magnetic flux $\lambda_m = L_m i_r$ of the WRSM [15], [16]. These parameters will be used for current control in the next section. The motor's equations can be written as:

$$\frac{di}{dt} = Ai + Bu + C \quad (14)$$

$$\text{where } i = [i_d \quad i_q]^T, u = [u_d \quad u_q]^T, A = \begin{bmatrix} -\frac{R_s}{L} & \omega \\ -\omega & -\frac{R_s}{L} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}, C = \begin{bmatrix} 0 \\ -\omega \frac{L_m i_r}{L} \end{bmatrix}$$

The estimated current \hat{i} model using parameters estimation can be written as follows:

$$\frac{d\hat{i}}{dt} = \hat{A}\hat{i} + \hat{B}u + \hat{C} + G(i - \hat{i}) \quad (15)$$

$$\text{where } \hat{A} = \begin{bmatrix} -\frac{\hat{R}_s}{\hat{L}} & \omega \\ -\omega & -\frac{\hat{R}_s}{\hat{L}} \end{bmatrix}, \hat{B} = \begin{bmatrix} \frac{1}{\hat{L}} & 0 \\ 0 & \frac{1}{\hat{L}} \end{bmatrix}, \hat{C} = \begin{bmatrix} 0 \\ -\omega \frac{\hat{\lambda}_m}{\hat{L}} \end{bmatrix}, G = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix}, K_1, K_2 > 0.$$

Subtracting (15) from (14):

$$\frac{d\hat{e}}{dt} = (A + G)\hat{e} + w \quad (16)$$

Where $\hat{e} = (i - \hat{i})$ and $w = (A - \hat{A})\hat{i} + (B - \hat{B})u + (C - \hat{C})$.

According to [17], to ensure stability, the two following conditions must be met:

1. The nonlinear feedback term satisfies Popov integral inequation: $\int_0^t w^T \hat{e} d\tau \geq -\gamma_0^2, \gamma_0 > 0$.
2. $K_1, K_2 \leq \frac{R_s}{L}$

Based on these two conditions, the estimated parameters can be defined as follows [15]:

$$\begin{cases} \frac{\hat{R}_s}{\hat{L}} = \frac{\hat{R}_s(0)}{\hat{L}(0)} - (K_{f2} + \frac{K_{f1}}{s})(i_d \hat{e}_d + i_q \hat{e}_q) \\ \frac{1}{\hat{L}} = \frac{1}{\hat{L}(0)} + (K_{g2} + \frac{K_{g1}}{s})(u_d \hat{e}_d + u_q \hat{e}_q) \\ \frac{\hat{\lambda}_m}{\hat{L}} = \frac{\hat{\lambda}_m(0)}{\hat{L}(0)} - (K_{h2} + \frac{K_{h1}}{s})(\omega \hat{e}_q) \end{cases} \quad (17)$$

Where $\hat{e}_d = i_d - \hat{i}_d$, and $\hat{e}_q = i_q - \hat{i}_q$. By using the transfer functions between the true parameters and their estimated values calculated in [17], we can define the values of $K_{f,g,h,1}$ and $K_{f,g,h,2}$ by plotting the roots. Figure 3 shows the diagram of the MRAS employed for WRSM parameters estimation.

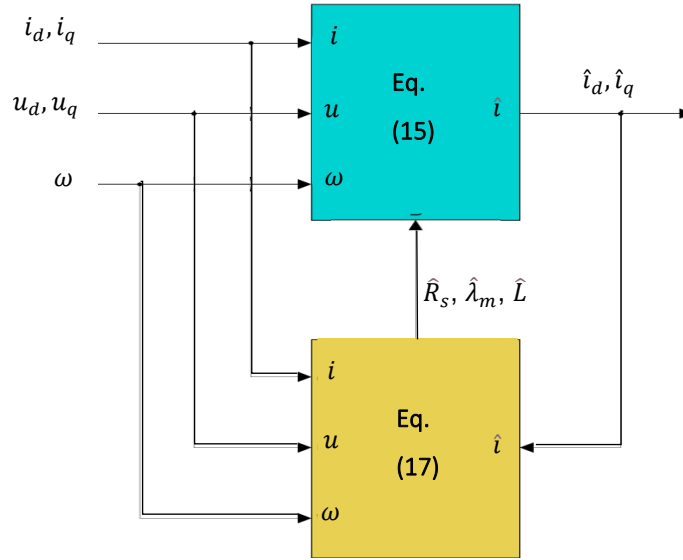


Figure 2 The diagram of the MRAS of WRMS parameters estimation

5. Adaptive Robust Control (ARC) for WRSM's Currents regulation

The wound rotor synchronous machine can be modeled using the following electrical equations:

$$\begin{cases} L \frac{di_q}{dt} = \varphi_q \theta_q + u_q \\ L \frac{di_d}{dt} = \varphi_d \theta_d + u_d \end{cases} \quad (18)$$

where $\varphi_q = [-i_q \quad -\omega i_d \quad -\omega]$, $\varphi_d = [-i_d \quad \omega i_q]$, $\theta_q = [R_s \quad L \quad L_m i_r]^T$ and $\theta_d = [R_s \quad L]^T$.

Let's consider $X = [x_d \quad x_q]^T = [i_d \quad i_q]^T$, $\varphi = \begin{bmatrix} \varphi_d & 0_{1 \times 3} \\ 0_{1 \times 2} & \varphi_q \end{bmatrix}$ and $\theta = [\theta_d \quad \theta_q]^T$.

With parameters variation, (18) can be written as follows:

$$L \frac{dX}{dt} = \varphi \theta + u + \Delta \quad (19)$$

where $\Delta = [\Delta_d \quad \Delta_q]^T$ represents the disturbance assumed to be present in the system. The adaptive robust current control algorithm is divided into two components [10]:

- An adaptive compensation u_a designed under the assumption of no disturbances ($\Delta = 0$).
- A robust regulator u_f specifically designed to address the presence of disturbances ($\Delta \neq 0$)

In case of no disturbances ($\Delta = 0$), u_a can be expressed as follows [17]:

$$u_a = L \frac{dX^*}{dt} - \varphi \hat{\theta} - k(X - X^*) = L \frac{dX^*}{dt} - \varphi \hat{\theta} - ke \quad (20)$$

In this context, X^* represents the desired reference value of X , $\hat{\theta}$ corresponds to the estimated parameters which will be extracted from MRAS of the previous section (instead of the mapped projection method [10], which is not precise in the high temperature applications), and $e = X - X^*$ defines the control error.

With disturbances ($\Delta \neq 0$), u_f is defined as:

Figures 6 and 7 show the rotor speed and the useful torque respectively. It can be observed that the proposed method improves the dynamics when the load torque is applied at $t = 1$ s. Between 8 and 10 s, the speed regulation is more robust in DOBC than in FOC, with fewer oscillations. During this period, the machine cools down, and the lost flux, estimated by \hat{D}_w , is recovered due to forced cooling.

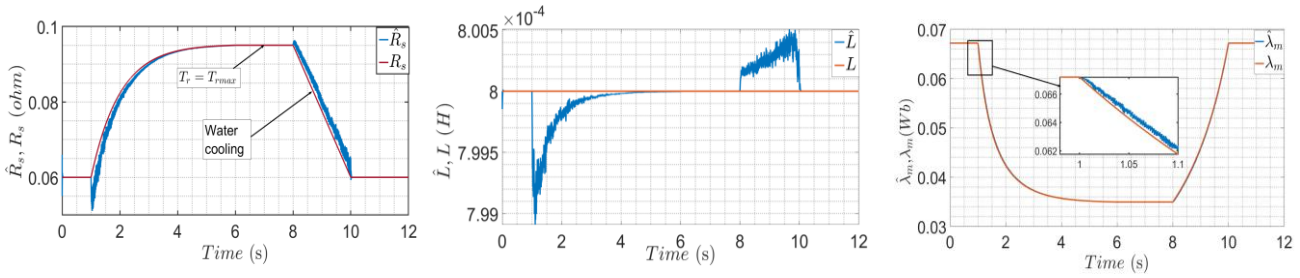


Figure 5. Estimated and actual value of (left to right): stator resistance, stator inductance and rotor flux.

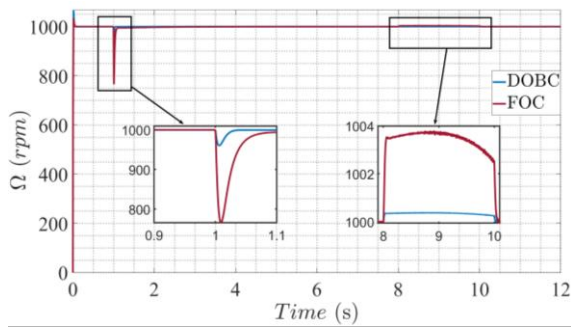


Figure 6. Simulation of regulated speed

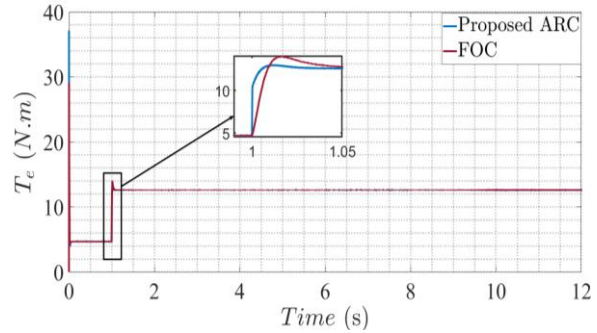


Figure 7. Simulation of output torque

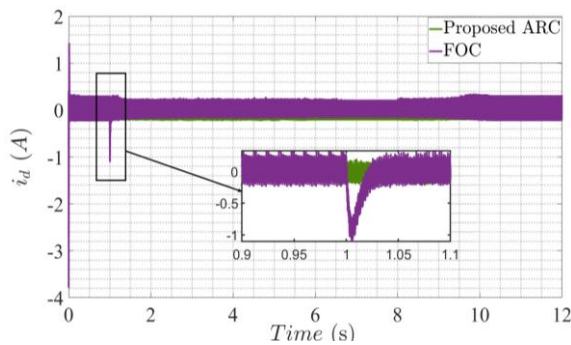


Figure 8. Simulation of controlled i_d

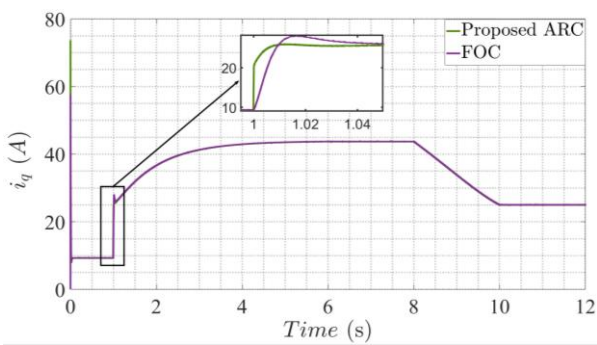


Figure 9. Simulation of controlled i_q

The currents i_d and i_q are shown in Fig.8 and Fig.9, where the use of proposed ARC demonstrates an improved dynamic response with ARC than with FOC in the two currents when the load torque is applied. The oscillations in i_d are reduced in the proposed method compared to FOC, while those in i_q are almost the same.

7. Conclusion

This paper introduces an adaptive robust current control method that uses a model reference adaptive system (MRAS) for estimating machine parameters, applied to a high-temperature anodized aluminum coils machine. The results are compared with the traditional Field Oriented Control (FOC) approach to evaluate how parameter variations affect speed and current control under varying temperatures. The findings show that using estimated parameters significantly improves the adaptability and robustness of current control, especially in transient conditions and high temperatures. Speed control is achieved with disturbance observer-based control, which performed better than the standard PI controller by handling parameter changes. The method was verified through MATLAB/Simulink simulations.

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