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Conceptual Cloud-Based Sliding Mode Speed Control for Synchronous Motors

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Abstract **-** In the development of control strategies for electric motors, current trends increasingly incorporate the Internet of Things and cloud computing technologies. This paper presents a conceptual control scheme based on sliding modes to regulate the speed of synchronous motors. The proposed control strategy, designed to track speed trajectories, is validated through simulations utilizing various sliding surfaces. The main contribution of this work is the integration of Internet of Things and cloud computing technologies with sliding mode control to enhance the efficiency and robustness of electric motor control. The proposed scheme offers a novel approach for advanced motor control systems, providing a robust framework for future practical applications.

***Keywords*:** cloud computing, synchronous motor, sliding mode control, Internet of Things, trajectory tracking

1. Introduction

The introduction of cloud computing and Internet of Things (IoT) in industrial systems has brought new solutions to control systems. The importance of these technologies lies in world environmental problems such as pollution, energy crisis, and traffic problems [1]. In this way, control systems can be integrated with these tools. In [2], predictive cruise control based on cloud computing is discussed in different scenarios for actual needs in electric vehicles. Also [3] explores how the traditional control systems can be improved with cloud technology addressing the main limitations such as scalability, starting, reconfiguration time, and algorithm complexity. A comparative study is performed in [4] to select the best devices for sensors and actuators in cloud computing. IoT is a way to interconnect intelligent physical devices from different systems. Their implementation in electrical motor drivers and wind energy generating systems improves the performance and monitoring through these tools as is shown in [5]. Cloud-based control systems have been improving their implementation in recent years. In 2016 some issues such as time delays, quantization, and others were important to addressing problems such as fault detection within a control scheme for DC motors and Permanent Magnets Synchronous Motor (PMSM) [6], [7]. However, three years later, new IoT devices and cloud computing solutions for control applications in different environments were introduced on the market. These technologies have improved their velocity and response to the previous problems as reviewed in [8].

One of the most important current applications for electric motors is in electric vehicles. The integration of IoT in these systems improves important tasks such as anomaly detection for future maintenance [9], and control systems for induction machines [10]. In this way, the sliding mode control increases its presence in electric motor drivers. This control technique is a robust and effective method to address non-linear systems where uncertainties and external unknown dynamical disturbances are present [11], [12]. A dynamic feedback control scheme for tracking planned motion in nonlinear PMSMs with uncertainty is addressed in [13], also classical control such as Proportional-Integral for tracking current trajectories in this electrical machine is addressed in [14]. Different systems that involve PMSM have been integrated with IoT technology for vibration monitoring, and fault detection [15]. Moreover, in [16] an adaptive sliding mode control to address the volatile nature of smart energy grids connected to wireless channels through IoT is proposed, to decrease the unstable communications on the grid. In addition, [17] proposes an intelligent proportional integral derivative current controller based on cloud computing to tune gains online with the chaos particle swarm optimization algorithm to estimate the rotor's position in a PMSM. In the last years, the introduction of Industry 4.0 and 5G networks implies less latency communication and in consequence improved applications in many environments mainly in the automotive industry. In this way, [18] summarizes some communication-control design methods based on cloud computing with an automated guide vehicle control design. Another cloud-based control application is shown in [19] for semi-active suspension for vehicles, where road information is obtained and processed in the cloud to update an adaptive control law.

Cloud-based control systems offer significant advantages over traditional implementations, such as the ability to store data in the cloud for improving control algorithms. This paper discusses a cloud-based speed sliding mode control scheme for synchronous motors. First, the controller is designed for tracking speed trajectories using the PMSM mathematical model and is simulated in Matlab to verify its robustness against external disturbances. Then, the possible devices for implementing this proposal are discussed, including Modbus serial communication that can be integrated within the microcontroller environment. The planned trajectories and different sliding surfaces could be stored in the cloud, for these purposes, the ASP server is reviewed for this specific application. This paper is organized as follows: Section 2 describes the speed control design for tracking speed trajectories. In Section 3, the proposed control scheme is presented and discussed with the integration of cloud computing and IoT devices. Section 4 analyzes the sliding mode control simulation results, and finally, the conclusions are presented in Section 5.

2. Sliding Mode Control for Tracking Speed Trajectories in PMSM

The PMSM system is described by Eqs. (1) - (3)

$$\frac{d}{dt}i_d = -\frac{R_s}{L_d}i_d + \frac{PL_q}{L_d}i_q\omega + \frac{1}{L_d}u_d \tag{1}$$

$$\frac{d}{dt}i_q = -\frac{R_s}{L_q}i_q - \frac{PL_d}{L_q}i_d\omega - \frac{P\lambda_m}{L_q}\omega + \frac{1}{L_q}u_q \tag{2}$$

$$J\frac{d}{dt}\omega = \frac{3}{2}P\lambda_m i_q - b\omega - \tau_L \tag{3}$$

i_d and i_q represent the electric current signals in the direct and quadrature axes, respectively, and the motor shaft angular velocity ω. L_d is the direct axis inductance, L_q is the quadrature axis inductance, R_s is the armature resistance, J is the moment of inertia, and b is the viscous damping coefficient. The number of pole pairs is indicated as P, and the magnetic flux of the permanent magnet is denoted by λ_m. τ_L describes the variable load torque affecting the motor rotor dynamics. For this study, it is assumed that $L_d = L_q$.

2.1. Controller Design

The potential of cloud computing is to analyze and store data using servers, databases, and software [5]. Data such as the sliding surfaces that the controller can use could be stored. Thus, the control system can be improved. In this way, different sliding surfaces can be chosen from those previously used in PMSM control. Traditional approaches such as Eqs. (4), and (5) where sliding surfaces are linear, or terminal SMC Eqs. (6), and (7) by introducing a non-linear part ensures asymptotic convergence [11]. These formulas can be stored in the cloud and each can be selected to adjust the controllers.

$$\sigma = ce + \frac{d}{dt}e \tag{4}$$

$$\sigma = e + \alpha\int e\,dt \tag{5}$$

$$\sigma = ce + \frac{d}{dt}e + \beta|e|^{\lambda} sign(e) \tag{6}$$

$$\sigma = \frac{d}{dt}e + \alpha e + \beta e^{\frac{q}{p}} \tag{7}$$

2.2. Direct – axis controller

It is assumed that both currents in the selected reference frame are available for measurement. Then, the direct-axis controller is designed. The error is considered as $e = i_d - i_d^\star$. To simplify the direct-axis controller a desired current is established as $i_d^\star = 0$. The desired controller dynamics is given by

$$\frac{d}{dt}\sigma_d = -W_d sign(\sigma) \tag{8}$$

any previous sliding surface can be selected, Eq. (5) is first chosen. Thus, by substituting (1) in (8) we obtain

$$-\frac{R_s}{L_d}i_d + \frac{PL_q}{L_d}i_q\omega + \frac{1}{L_d}u_d - \frac{d}{dt}i_d^\star + \alpha e = -W_d\, sign(\sigma_d) \tag{9}$$

from the last Equation, the direct-axis controller is given as

$$\frac{1}{L_d}u_d = \frac{d}{dt}i_d^\star + \frac{R_s}{L_d}i_d - \frac{PL_q}{L_d}i_q\omega - \alpha e - W_d sign(\sigma_d) \tag{10}$$

2.3. Quadrature – axis controller

Eq. (3) is derived with respect to the time obtaining

$$\frac{d^2}{dt^2}\omega = \frac{3}{2}\frac{P\lambda_m}{J}\frac{d}{dt}i_q - \frac{b}{J}\frac{d}{dt}\omega - \frac{1}{J}\frac{d}{dt}\tau_L \tag{11}$$

then, Eq. (2) is substituted in the previous Equation obtaining

$$\frac{d^2}{dt^2}\omega = -\frac{3}{2}\frac{P\lambda_m R_s}{JL_q}i_q - \frac{3}{2}\frac{P^2\lambda_m L_d}{JL_q}i_d\omega - \frac{3}{2}\frac{P^2\lambda_m^2}{JL_q}\omega + \frac{3}{2}\frac{P\lambda_m}{JL_q}u_q - \frac{b}{J}\frac{d}{dt}\omega - \frac{1}{J}\frac{d}{dt}\tau_L \tag{12}$$

for tracking trajectories the error takes the form $e = \omega - \omega^\star$, for speed regulation in PMSM terminal SMC sliding surface from Eq. (6) can be selected also to improve the controller robustness against disturbances. Then, the desired dynamics for the quadrature-axis is

$$\frac{d}{dt}\sigma_q = -W_q sign(\sigma_q) \tag{13}$$

substituting (12) in (13) we obtain

$$
-\frac{3}{2}\frac{P\lambda_m R_s}{JL_q i_q} i_q - \frac{3}{2}\frac{P^2\lambda_m L_d}{JL_q} i_d\omega - \frac{3}{2}\frac{P^2\lambda_m^2}{JL_q}\omega + \frac{3}{2}\frac{P\lambda_m}{JL_q}u_q - \frac{b}{J}\frac{d}{dt}\omega - \frac{1}{J}\frac{d}{dt}\tau_L - \frac{d^2}{dt^2}\omega^\star + c\frac{d}{dt}e + \frac{d}{dt}\left[\beta|e|^\lambda sign(e)\right] = -W_q\, sign(\sigma_q) \tag{14}
$$

consequently, the quadrature-axis controller is obtained as follows:

$$
\frac{3}{2}\frac{P\lambda_m}{JL_q}u_q = \frac{d^2}{dt^2}\omega^\star + \frac{3}{2}\frac{P\lambda_m R_s}{JL_q} i_q + \frac{3}{2}\frac{P^2\lambda_m L_d}{JL_q} i_d\omega + \frac{3}{2}\frac{P^2\lambda_m^2}{JL_q}\omega + \frac{b}{J}\frac{d}{dt}\omega + \frac{1}{J}\frac{d}{dt}\tau_L - c\frac{d}{dt}e - \frac{d}{dt}\left[\beta|e|^\lambda sign(e)\right] - W_q sign(\sigma_q) \tag{15}
$$

3. Cloud-based control scheme

Different devices can be implemented to work in cloud environments and IoT such as microcontrollers, FPGAs, and others. Within industrial automation, these technologies help to control and monitor machines with good efficiency [8]. Wireless devices can be integrated to reduce the computing cost on these boards. For electric machines, different stages must be considered within cloud-based control strategies.

3.1. Controller algorithm and devices

The devices required to develop control algorithms for electrical machines should be able to process a great quantity of information. Boards such as microcontrollers, FPGAs, and DSPs are used to develop motor converters. In addition, the main devices included in motor control are inverters, which in turn need a filter stage. To compute speed or motor's position encoder is usually implemented. Current PWM techniques need currents information which can be obtained with sensors and can be processed in the control device this relation is depicted in Figure 1.

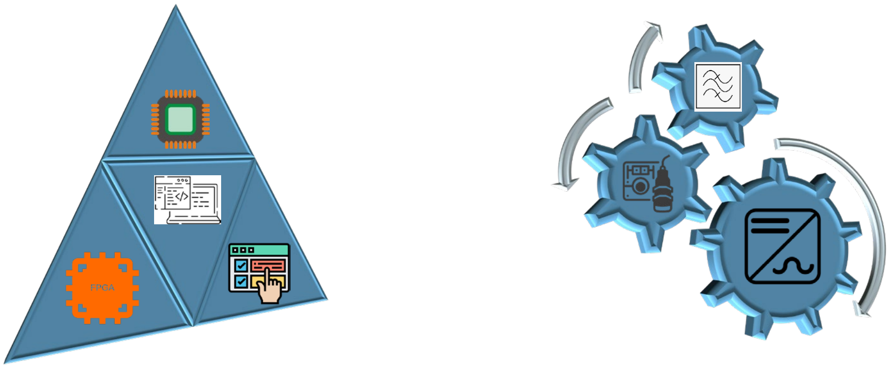

Fig. 1: Necessary devices to program control algorithms for rotational machines.

3.2. Serial Communication and Cloud Server

A cloud-based control scheme needs a communication protocol to send and receive information. Modbus serial communication is a protocol that has been used widely for connecting industrial devices with Programmable Logic Controllers (PLCs). In simple terms, it is a method used for transmitting information over serial lines between electronic devices. The device requesting the information is called the Modbus Client and the devices supplying information are Modbus Servers. In a standard Modbus network, there is one Client and up to 247 Servers, each with a unique Server Address from 1 to 247. The Client can also write information to the Servers. And, nowadays different devices have been developed to integrate them to operate within a cloud environment figure 2 displays the basic architecture of this protocol.

Also, using a server like ASP.NET for a cloud-based control scheme is a possible choice. ASP.NET, an open development server, offers a robust platform for building and deploying applications that require cloud integration. The asp.net application codes can be written in any language such as C\#, Visual Basic, or Java Script. Different microcontroller microcontroller architectures work within these environments [5].

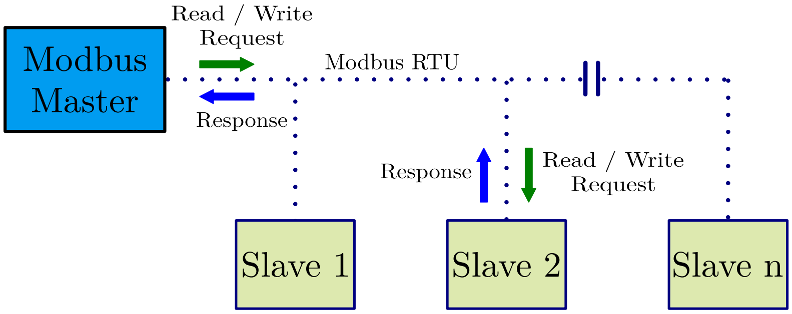

Fig. 2: Basic scheme of Modbus Serial Communication.

3.3. Proposed control scheme

Once the cloud-based control requirements have been analyzed, the diagram in Figure 3 illustrates how Modbus communication and a cloud server can be integrated with a microcontroller to perform a speed control strategy for synchronous motors. Suppose that the control device is a microcontroller, such as an ESP-32, to develop a cloud-based platform for PMSM. According to the controllers obtained in section 2, it is assumed that the i_d current and speed ω are available for measurement. Then, the control signals u_d and u_q are necessary to generate the gate signals for the transistors.

The planned trajectories and sliding surfaces can be stored in the cloud during the initial microcontroller task, along with variable declarations and input-output configurations. By doing this, the main program can be executed to generate the gate signals and obtain the three-phase voltages required by the electrical machine.

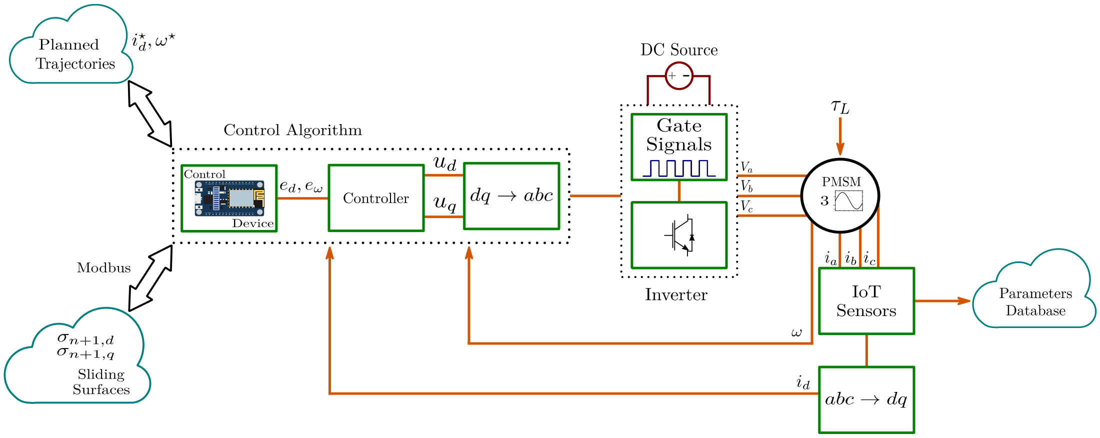

Fig. 3: Proposed cloud-based sliding mode control for tracking speed trajectories of a PMSM.

The bidirectional communication between the control device and the cloud is considered as follows: The planned trajectories and the sliding surfaces can be programmed within the microcontroller interface and sent to the cloud for storage, reducing the code lines on the microcontroller. Additionally, using a different programming application such as ASP.NET, the same information can be stored and sent to the microcontroller through Modbus communication.

Moreover, IoT devices such as current sensors can be used to read the signals and integrate them into the control algorithm. The device can send information through any communication interface to store a database for monitoring the control process, as demonstrated in [8].

4. Simulation results

Finally, the controller is evaluated through simulations to validate the control laws. The speed trajectory reference $\omega^\star$ is proposed by Bezier polynomials and is defined as shown in Eq. (16). Multiple speed trajectories can be stored in the cloud, and can be selected when the system is initiated decreasing costs, time, and code lines

$$\omega^\star = \begin{cases} \overline{\omega}_1 & for\ 0 \le t < t_1 \\ \overline{\omega}_1 + (\overline{\omega}_2 - \overline{\omega}_1)\mathfrak{B}_\omega & for\ t_1 < t < t_2 \\ \overline{\omega}_2 & for \quad t \ge t_2 \end{cases} \tag{16}$$

for this case $\overline{\omega}_1 = 0$ rad/s, $\overline{\omega}_2 = 230.383$ rad/s (2200 rpm), $t_1 = 0$ s, $t_2 = 2$ s, $\mathfrak{B}_\omega$ is the Bezier curve described by

$$\mathfrak{B}_\omega = \sum_{k=1}^{9} r_k \left(\frac{t - t_1}{t_2 - t_1}\right)^{2+k} \tag{17}$$

the system response is shown in Figure 4, notice that the controller has good behavior since the trajectory is tracked adequately, an oscillatory torque load is proposed as $\tau_L = 2.5 \sin \omega t$. Moreover, to address the chattering problem, recently a study to substitute the standard sign function with a continuous approximation demonstrates the effective mitigation of this phenomenon [20]. The selected approximation is

$$sign(\sigma) = \frac{\sigma}{\sqrt{\sigma^2 + \epsilon}} \tag{18}$$

as figure 4 shows, the sign function approximation integration in both controllers helps to reduce the chattering problem, and the control has a good response against the torque load, in this case $\epsilon = 2000$.

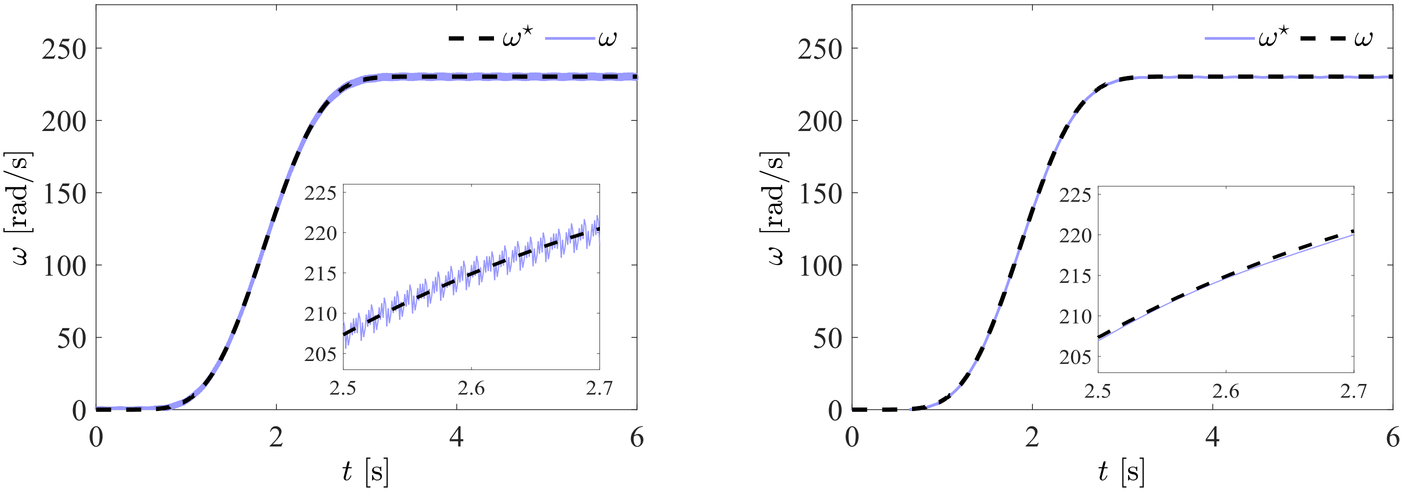

Fig. 4: Synchronous Motor Speed Response with chattering phenomenon, and mitigated chattering.

Figure 5 displays the generated voltages in the direct-axis and quadrature-axis respectively.

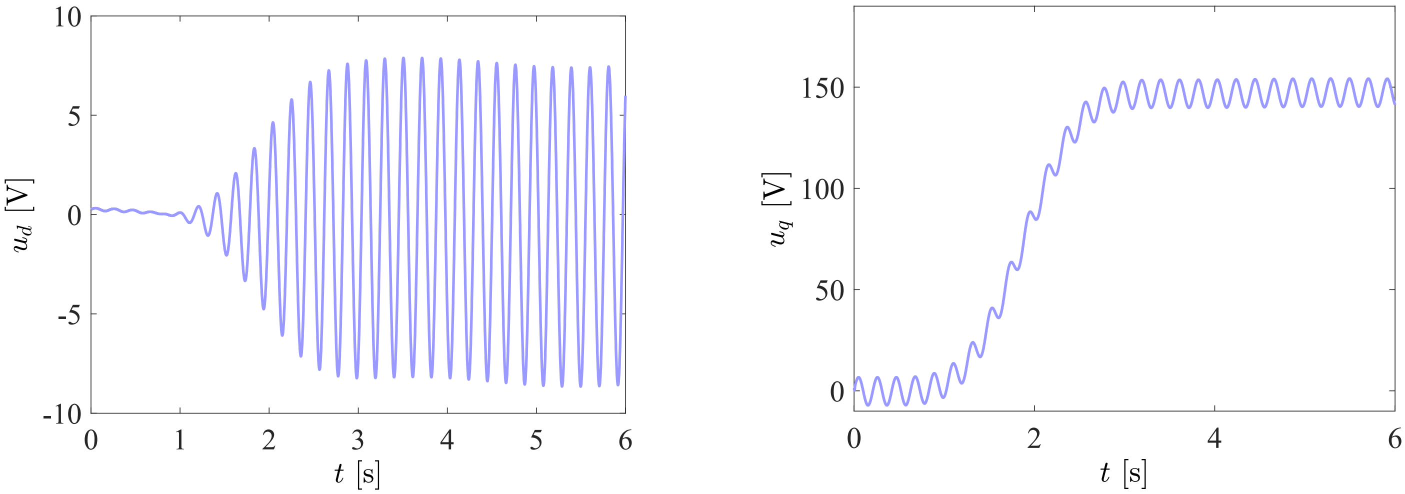

Fig. 5: Direct-axis voltage and quadrature-axis voltage.

5. Conclusions

In this study, a conceptual analysis of a cloud-based control scheme for the speed regulation of Permanent Magnet Synchronous Motors was proposed. The control scheme's various stages were examined, starting with the integration of a microcontroller and Modbus communication to store essential control algorithm information such as sliding surfaces and planned trajectories. For monitoring purposes, IoT sensors were considered to transmit relevant data and generate a cloud-based database, with the ASP server reviewed for this application. A sliding mode speed control was designed to track speed profiles, and the control scheme was validated through simulations using Matlab software. Future work will involve the physical implementation of the complete control scheme, leveraging cloud and IoT technologies to enhance the efficiency and robustness of PMSM control systems.

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