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An Intelligent Nonlinear Control Approach Based on Fuzzy Logic for Permanent Magnet Synchronous Machine

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***Abstract*—This work focuses on improving the dynamic performance of Permanent Magnet Synchronous Machines (PMSM) through advanced control strategies. PMSMs are increasingly used in industry due to their advantages, such as low rotor inertia, efficient heat dissipation, and high torque density. Unlike traditional DC motors, PMSMs require an inverter synchronized with the rotor position for proper operation. While DC motors are easier to control, PMSMs offer better robustness and power-to-weight ratio, making them suitable for modern industrial applications. To address this, the study investigates different control strategies for PMSM speed regulation. Numerical simulations are conducted to evaluate the performance of various controllers, including classic PI controllers, fuzzy logic controllers, and adaptive fuzzy controllers. The aim is to enhance dynamic response, ensure stability, and improve overall control performance in industrial applications.**

***Keywords*—Permanent magnet synchronous machine, classic PI controllers, fuzzy logic controllers, adaptive fuzzy controllers.**

I. Introduction

Permanent Magnet Synchronous Machines (PMSM) are increasingly used in industry because they offer many advantages: low rotor inertia, efficient heat dissipation and high specific torque. In addition, the elimination of brushes reduces noise and eliminates the need for their maintenance. Current research aims to replace Direct Current Machines (DCM) with (PMSM) in the industrial field initially occupied by the control of MCCs. The DC motor is powered by a simple static converter and a regulation of its armature current allows to control its torque. For the PMSM, the collector function is performed by an inverter synchronized with the rotor position [1], [2].

However, its main defect is the mechanical collector, which can be annoying in certain environmental situations, as well as the increase in maintenance costs. These constraints have influenced the result, studies oriented towards drives with AC machines. For all these reasons, the orientation towards research leading to better exploitation of a robust actuator is very justified, namely, the cage asynchronous motor and the permanent magnet synchronous motor (PMSM), which are robust and have a simple construction that limits the cost and increases the mass power ratio. This is why AC machines are increasingly replacing DC motors in many fields such as servomotors [3].

New industrial applications require speed variators with high dynamic performance, good steady-state accuracy, high overload capacity over the entire speed range and robustness to different disturbances. In recent years, several techniques have been developed to enable the variator to achieve these performances [3].

Vector control is a method that reduces to a linear control structure by the hypothesis of flux orientation. It was proposed by Blaschke in 1972. Although this method remained little used until the early 1980s, the progress currently made in semiconductor technology and microelectronics has allowed its use in current industrial speed controllers. This control allows for dynamics close to that of the DC machine, in other words, asymptotically linear and decoupled dynamics. However, this control structure using conventional PI-type regulators requires that the machine parameters be precise (internal and external parametric variations of the system due to temperature, humidity, and occasional overloads cause the loss of stability of the conventional regulators considered). This requires good identification of the parameters. Consequently, the use of robust control regulators, to maintain an acceptable level of decoupling and performance, is necessary [4], [5].

In order to improve the dynamic performance of the speed adjustment of the MSAP, we have presented in this work, by numerical simulation, the speed control of a permanent magnet synchronous machine supplied with voltage, with flux orientation, by regulators of different algorithms (classical PI regulators, fuzzy regulators and adaptive fuzzy regulators).

II. PMSM MODEL

The permanent magnet synchronous machine is a nonlinear system with a lot of moving parts. To have adequate control over this machine in various working modes, one needs a precise and demanding mathematical modeling to accurately and realistically reflect its behavior [6, 7].

$$\begin{cases} \frac{dI_d}{dt} = \frac{1}{L_d}\left(V_d - R_s I_d + \omega L_q I_q\right) \\ \frac{dI_q}{dt} = \frac{1}{L_q}\left(V_q - R_s I_q - \omega L_d I_d - \omega \emptyset_f\right) \\ C_{em} = \frac{3}{2} p \left[\left(L_d - L_q\right) I_d \, I_q + \emptyset_f I_q\right] \\ \frac{d\Omega}{dt} = \frac{1}{J}\left(C_{em} - C_r - f\Omega\right) \end{cases} \quad (1)$$

Where: $\omega = p\Omega$ and Ω, C_{em}, C_r are the speed, the electro-magnetic torque, and the resisting torque. The subscript s refer to stator.

PMSM-based systems require the use of a static converter (inverter) that powers the machine stator. The major goals of this converter are to undulate the DC bus voltage so that it may be supplied to the stator winding and to allow commands to be applied to regulate the mechanical powers generated by the rotor of this machine.

The voltage inverter is a two-level device with several semiconductor devices that control the opening and closing of the circuit.

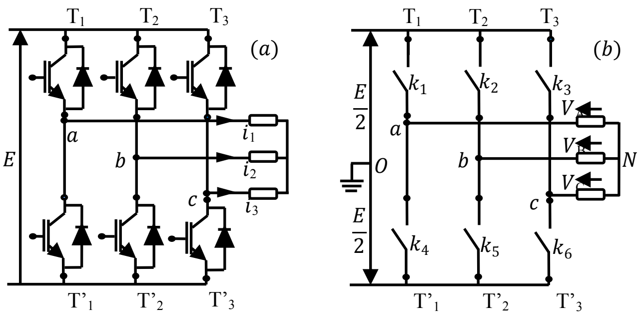


Fig. 1. Simplified diagram of the two-level three-phase inverter.

After development mathematic in [1], the stator side converter's mathematical model is as follows:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{E}{6} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (2)$$

Control by pulse width modulation (Sine-Triangle PWM) consists in converting the modulation (the reference voltage to the control level generally a sinusoid) into a voltage in the form of continuous pulses produced at the output of the inverter (power level). The technique is based on a comparison between two signals [8]:

The first is called the reference signal and represents the desired sinusoidal image at the output of the inverter. The signal is amplitude and frequency modulated. The second, called the carrier signal, defines the switching rate of the inverter static switches. It is a high frequency signal compared to the reference signal. The intersection of these signals gives the switching, instant of the switch.

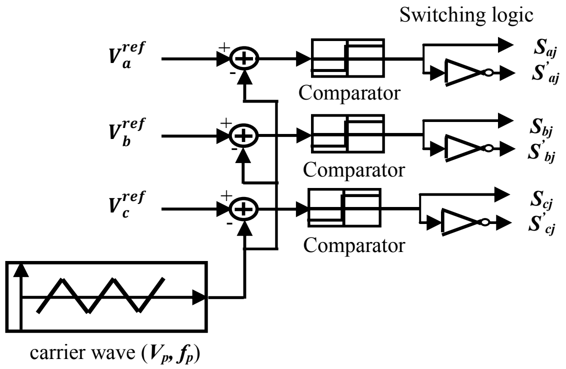


Fig. 2. Sine-triangle PWM.

III. VECTOR CONTROL APPLIED TO THE PMSM

The control of AC machines is difficult because there is a complex coupling between flux and torque. This difficulty has encouraged the development of several control techniques to make these machines behave like DC machines, characterized by a natural decoupling of flux and torque. Among these control techniques is vector control [7, 9].

Vector control based on a classic regulation (Proportional Integral), combines in its structure compensation terms which allow to decouple the axis (which will be used for the adjustment of the flux), from the axis (which will be used for the adjustment of the torque). This configuration allows to realize electric actuation systems having the performances required by the fields of application [10].

Among the control strategies, one that often uses is the one that consists of keeping the I_d component zero. This strategy allows for a simplified control law with a linear relationship between torque and current. This results in a characteristic similar to that of the separately excited DC machine [9].

If the current I_d is forced to zero ($I_d = 0$), the stator flux component becomes:

$$\emptyset_d = \emptyset_f \quad (3)$$

The expression of the torque becomes:

$$C_{em} = \frac{3}{2} p \emptyset_f I_q \quad (4)$$

As the flux $\emptyset_f$ is constant, the torque is directly proportional to I_q. Therefore:

$$C_{em} = K_t I_q \quad (5)$$

With :

$$K_t = \frac{3}{2} p \, \emptyset_f$$

The most frequently used strategy is to maintain the armature reaction flux in quadrature with the rotor flux, or the magnets are replaced by a winding crossed by a constant current I_f producing a flux equivalent to that of the magnets [11].

The model of the machine in the Park frame becomes:

$$V_d = -\omega_r L_q I_q$$
$$V_q = R_s I_q + L_q \frac{dI_q}{dt} + \omega_r \phi_f \qquad (6)$$

Figure (3) represents the overall diagram of a speed regulation of the permanent magnet synchronous machine in the (d, q) frame. The machine being decoupled along two axes (d, q), the regulation on the d axis is done by a single loop, while the regulation on the q axis is done by two cascaded loops, one internal to regulate the current and the other external to regulate the speed.

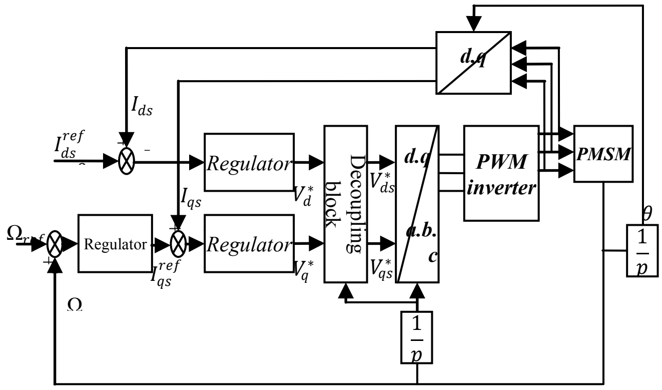


Fig. 3. Block diagram of a PMSM speed control.

IV. ADAPTIVE FUZZY LOGIC CONTROL APPLIED TO PMSM

Artificial intelligence techniques, particularly fuzzy logic, are currently known for their great potential to solve problems related to industrial processes, estimation and identification of the parameters of varying systems. They can be used wisely for their qualities to resolve certain problems related to both modeling errors and the lack of knowledge of the model of the controlled system. A PI controller will be a fuzzy controller (Fuzzy Logic Controller "FLC"), i.e. a fuzzy PI, has the ability to improve the dynamic and static performance of a loop control, in particular for improving the robustness of a control against modeling errors and parametric drifts, which are often inevitable.

A. Adaptive Control

The term "adaptive control" refers to a set of methods that allow the automatic, real-time adjustment of controller parameters implemented in a control loop to achieve or maintain a desired performance level when the controlled process is not well known or has significant nonlinearity or time-varying parameters [12].

Although every controller is adaptive in the sense that it changes its output whenever the error changes, true adaptive control is when the controller adapts not only its output but also its control strategy [12].

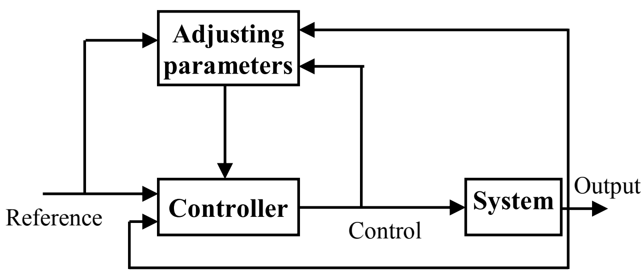


Fig. 4. Block diagram of an adaptive control

B. Adaptive Fuzzy Control

The internal structure of the fuzzy logic adaptation mechanism is identical to that of an FLC. It consists of three blocks: Fuzzification (F), Inference (I), Defuzzification (D). shows the fuzzy logic adaptation mechanism. In the block diagram, we have: the error E and its derivative DE are defined by:

$$E(t_s) = Y_{ref}(t_s) - Y_{mes}(t_s) \qquad (7)$$

$$DE(t_s) = E(t_s) - E(t_s - 1) \qquad (8)$$

The reference model represents the system dynamics with nominal parameters. For a complex system like PMSM, it is very difficult to construct exact nominal dynamics, due to its high order and nonlinearity.

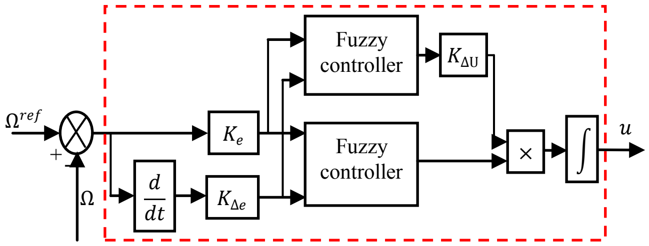


Fig. 5. Block diagram of an adaptive speed fuzzy controller

The choice of linguistic variables is represented by: Large negative noted NG; Medium negative noted NM; Small negative noted NP; Around zero noted EZ; Small positive noted PP; Medium positive noted PM; Large positive noted PG.

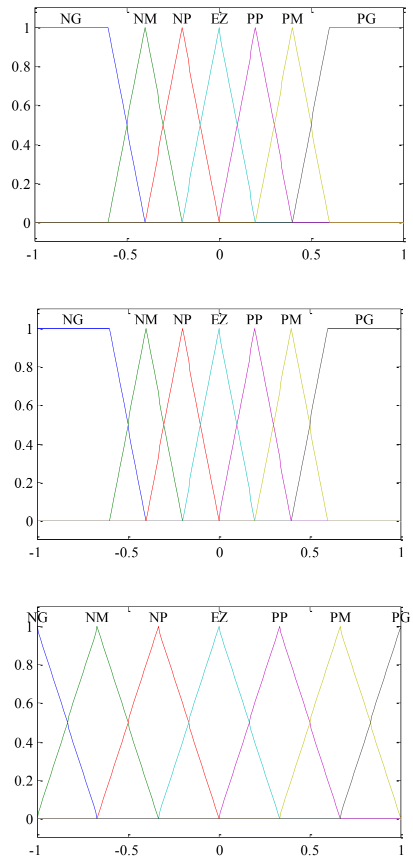


Fig. 6. Membership functions used by the control (e, Δe and control)

The inference rules for determining the output variable for current adjustment are grouped in the table below. The inference method used is Mamdani's "min-max" method.

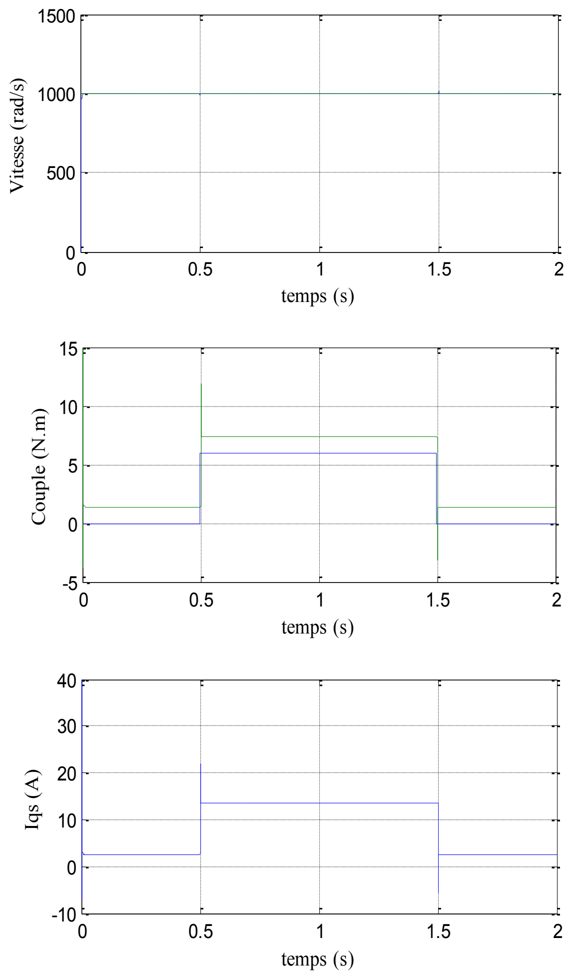
TABLE I. DECISION RULE TABLE FOR THE SPEED CONTROLLER

Control		**Error**						
		NG	NM	NP	EZ	PP	PM	PG
Derived from error	NG	NG	NG	NG	NG	EZ	EZ	EZ
	NM	NG	NG	NM	NM	EZ	EZ	EZ
	NP	NG	NG	NP	NP	PP	PP	PM
	EZ	NG	NM	NP	EZ	PP	PM	PG
	PP	NM	NP	NP	PP	PP	PG	PG
	PM	EZ	EZ	EZ	PM	PM	PG	PG
	PG	EZ	EZ	EZ	PG	PG	PG	PG

V. SIMULATION AND INTERPRETATION OF RESULTS

In order to test the performance of adaptive fuzzy control applied to an PMSM, we simulated the operation of the inverter-machine assembly and The simulation was carried out under the Matlab/Simulink environment by a block diagram. The machine parameters are presented in the appendix.

To verify the effectiveness of the adaptive fuzzy control, in this test we apply a load of value (Cr=6N.m) between the instants t = 0.5s and t = 1.5s. The corresponding simulation results are grouped in figure (7).



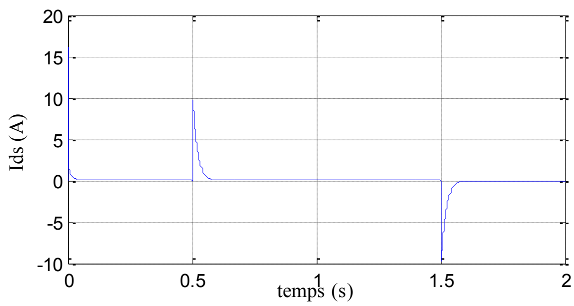


Fig. 7. The shape of the MSAP quantities during adaptive fuzzy control with application of a load of 6 N.m from 0.5s to 1.5s.

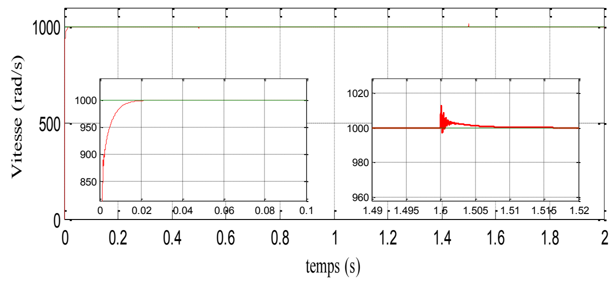


Fig. 8. Zoom in on speed versus time with application of a load of 6 N.m from 0.5s to 1.5s (Adaptive fuzzy control).

Applying the adaptive control resulted in an improvement in Dynamic Performance of Transient Systems related to all tests. It is noted that:

- The speed follows its reference value, with an overshoot during the transient state. After the load is applied,
- at time t=0.5s, the speed drops, which is rejected, then returns to its reference value.
- at t=1.5s, the speed increases, which is also rejected, then returns to its reference value.
- The torque peaks at the first moment of start-up, then reaches the resistive torque value before and after the load is applied.
- The response of the two current components clearly demonstrates the decoupling introduced by the machine's adaptive fuzzy control ($I_d = 0$).
- The current I_q is the image of the torque.

VI. CONCLUSION

An adaptive controller is a regulator that can modify its behavior in response to changes in the dynamics of a system and disturbances, or it consists of eliminating structural disturbances (variations in parameters) acting on the performance of the control system. Following its application, it is found that the adaptive fuzzy control has a good dynamic speed response and a very good disturbance rejection.

The simulation results show the improvement of the dynamic performance of the machine and decrease the disturbances in the transient regime, in particular the current and torque peaks which have been considerably reduced. To cope with the problem of calculating fuzzy gains, we have built an adaptation mechanism on the application to determine the real values of the gains of a fuzzy PI.

APPENDIX

TABLE II. PARAMETERS OF THE PMSM

Parameters	Value	Parameters	Value
R_s	1.67 Ω	L_d	0.00145 H
$\emptyset_f$	0.17 Wb	Ω	157 rad/s
P	3	L_q	0.00145 H
f	0.013	J	0.0003 $Kg.m^2$

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