1. Abdelghafour HERIZI[1,2], 2. Riyadh ROUABHI[1,2], 3. Abderrahim ZEMMIT[1]

Electrical Engineering Department, University of M'sila, Algeria (1)
LGE Research Laboratory of M'sila (2)

doi:10.15199/48.2022.11.03

Comparative study of the performance of a sliding, sliding-fuzzy type 1 and a sliding-fuzzy type 2 control of a permanent magnet synchronous machine

***Abstract**. This paper presents a comparative study of sliding mode control, hybrid sliding type-1 fuzzy logic and hybrid sliding type-2 fuzzy logic applied on the permanent magnet synchronous machine (PMSM). We used different criteria in this comparison: qualitative, quantitative and robust during the transient and permanent operation of the system. In this article, we present a new sliding mode control strategy applied to the PMSM, this control combines sliding mode and fuzzy logic (type-1 and type-2) to find robust control. The control proposed keeping the part of the equivalent control by sliding mode and will change the part of the switching by a fuzzy controller. Simulation results with a sliding mode control, type-1 fuzzy logic controller (T1FLC) and with an interval type-2 fuzzy logic controller (IT2FLC) of a permanent magnet synchronous machine are presented. The advantage of using interval type-2 fuzzy logic controller is verified.*

***Streszczenie**. W artykule przedstawiono badanie porównawcze sterowania ślizgowego, hybrydowej ślizgowej logiki rozmytej typu 1 i hybrydowej ślizgowej logiki rozmytej typu 2 zastosowanej w maszynie synchronicznej z magnesami trwałymi (PMSM). W tym porównaniu zastosowaliśmy różne kryteria: jakościowe, ilościowe i solidne podczas przejściowej i stałej pracy systemu. W tym artykule przedstawiamy nową strategię sterowania trybem ślizgowym zastosowaną do PMSM, ta kontrola łączy tryb ślizgowy i logikę rozmytą (typu-1 i typu-2), aby znaleźć niezawodne sterowanie. Sterowanie zaproponowało zachowanie części sterowania równoważnego w trybie przesuwnym i zmieni część przełączania za pomocą sterownika rozmytego. Przedstawiono wyniki symulacji ze sterowaniem ślizgowym, regulatorem rozmytym typu 1 (T1FLC) oraz interwałowym regulatorem logiki rozmytej typu 2 (IT2FLC) maszyny synchronicznej z magnesami trwałymi. Sprawdzono zaletę stosowania interwałowego sterownika rozmytego typu 2. (**Badanie porównawcze działania przesuwnego, ślizgowo-rozmytego typu 1 i ślizgowo-rozmytego typu 2 maszyny synchronicznej z magnesami trwałymi**)*

Keywords: Permanent magnet synchronous machine, sliding mode control, Type-1 fuzzy logic, Interval Type-2 Fuzzy Logic.
Słowa kluczowe: Maszyna synchroniczna z magnesami trwałymi, sterowanie trybem przesuwnym, logika rozmyta typu 1, logika rozmyta typu 2 interwału.

1. Introduction

The control of electric machines is the most active field, especially in recent years, and the reason is that electric machines are the inexpensive and least bulky engine of industrial motors. What distinguishes the separately equipped DC machine is its ease of use. In fact, we separate and control flow and torque independently, which allows high dynamic performance can be achieved. However, the presence of the mechanically complex reduces the areas of its use [1, 2].

In the industrial environment, permanent magnet synchronous motors (PMSM) are also recommended. This is due to the fact that they are more simple, reliable, and compact than DC motors [3 - 5]. Thus, their construction is simpler since they do not have mechanical switches. Consequently, this increases their lifespan and avoids permanent maintenance. They can be used in an explosive environment because no spark is produced. They can also provide significant power in relation to their mass unlike DC machines which require more power sources and have a lower specific power [6, 7]. Thanks to these technical qualities, there is a lot of interest in the literature at MSAP in robotics, traction system, space technology and in domestic applications [8 - 10].

From the design point of view of electrical automatic control systems for MSAPs, we are always looking to improve their performance. Conventional control algorithms, for example, proportional-integral action, may be sufficient if the requirements on system accuracy and performance are not too stringent. Otherwise, and particularly when the controlled part is subject to strong non-linearities and temporal variations, it is necessary to design control techniques, ensuring the robustness of the process vis-à-vis the uncertainties on the parameters and their variations. Among these techniques, there is control by sliding mode, it is a robust control linked to systems with variable structures, the purpose of which is to overcome the disadvantages of conventional controls [11, 12], since the control with variable structures is by nature a control, nonlinear and that their control law changes in a discontinuous way [5], [13, 14].

On the other hand, significant progress has been made over the last two decades. In fact, new methods like fuzzy logic, neural networks, genetic algorithms, and others have made it possible for a brand-new field of study called artificial intelligence to develop. Artificial intelligence approaches have allowed researchers to not only improve system control and overcome the limitations of traditional methods, but also to radically transform the concepts employed in the study and design of control systems. The above-mentioned strategies have the distinct benefit of being more directed toward the approximation of systems rather than the search for their precise models [15, 16].

Fuzzy logic, which is an intelligent technique, has been used successfully [17]. Its strong point is its robustness, given that the fuzzy decision is based on vague appreciations, which do not even require a precise knowledge of the model of the system to be controlled. The association of the fuzzy control with the sliding mode makes it possible to have the advantages of these two techniques. This gives the advantage of being able to separately control the flux and the torque [18].

In light of what has been discussed, we suggest in this paper a link between sliding mode control and type-1 and type-2 fuzzy logic. In order to enhance the dynamic responses of the permanent magnet synchronous machine, this association will be used to create new, robust controls based on fuzzy logic.

The article is structured as follows: Initially, a dynamic model of the MSAP was proposed in the reference of Park (d, q) which allows the setting in the form of an equation of state of the machine fed in tension. Then, a sliding mode control strategy of the permanent magnet synchronous machine which allows independent control of flux and torque. In the fourth section, we synthesize a sliding type-1 fuzzy and type-2 fuzzy control law of the PMSM. Finally, a comparative study to examine the different laws of the developed and synthesized controls of the permanent magnet synchronous machine, we will present a qualitative, quantitative and robust comparative study between its different techniques. This comparison is based on a series of experiments performed throughout the system's transitory and permanent operation.

2. 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 [5, 19].

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

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.

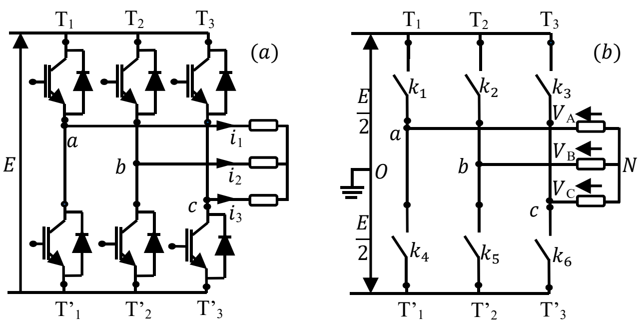

Fig.1. Simplified diagram of the two-level three-phase inverter.

After development mathematic in [5], the stator side converter's mathematical model is as follows:

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

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 [20]:

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.

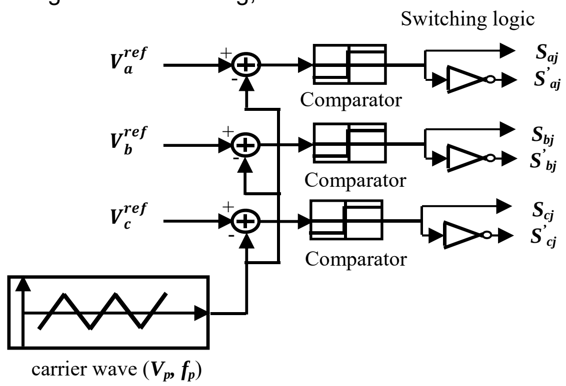

Fig.2. Sine-triangle PWM.

3. Sliding mode control

The basic idea of SMC is to first draw the machine's states into a clearly defined region, then design a control regulation to keep the machine in that region [5], [21]. In summary, an SMC is made up of three parts:

3.1 Choice of switching surface

With regard to a non-linear system shown in the following manner:

$$(3)\quad \begin{array}{l} \dot{x} = f(x,t) + g(x,t).u(x,t) \\ x \in R^n, u \in R \end{array}$$

Where: $f(x,t)$ and $g(x,t)$ are continuous and ambiguous nonlinear functions, respectively, and mean limited.

We use the shape of the fashionable equation given by J.J. Slotine [22] to get the sliding surface given by using:

$$(4)\quad \begin{array}{l} s(x) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \\ e = x^d - x \end{array}$$

Where: λ is the positive coefficient, e is the signal error to be modified, and n is the system order.

To synthesize the sliding mode control of the PMSM, we choose the following surfaces:

$$(5)\quad \begin{cases} S_1(\Omega) = \Omega_{ref} - \Omega \\ S_2(I_q) = I_q^{ref} - I_q \\ S_3(I_d) = I_d^{ref} - I_d \end{cases}$$

3.2 Convergence condition

The Lyapunov equation [23] is used to characterize the convergence situation, which makes the region appealing and invariant.

$$(6)\quad s(x)\dot{s}(x) < 0$$

To ensure the convergence condition, the sliding surfaces must be zero:

$$(7)\quad \begin{cases} S(\Omega) = 0 \\ S(I_q) = 0 \\ S(I_d) = 0 \end{cases} \Rightarrow \begin{cases} \frac{d}{dt}\left(\Omega_{ref} - \Omega\right) = 0 \\ \frac{d}{dt}\left(I_q^{ref} - I_q\right) = 0 \\ \frac{d}{dt}\left(I_d^{ref} - I_d\right) = 0 \end{cases}$$

When the convergence conditions are satisfied, the speed and the currents tend exponentially towards their reference values, and to follow these values, it suffices to make the sliding surface attractive and invariant.

3.3 Control calculation

The relationship: is used to describe the control set of rules:

(8) $u = u^{eq} + u^{n}$

Where: u^{eq} : is the equal control vector and u^{n} : is the control's switching component (the correction factor).

J. J. Slotine developed a solution to reduce the undesirable chattering phenomena by utilizing the switching surface's "$sign$" function [22]. The control u^{n} switching component is described with the following:

(9) $u^{n} = k\,sign\big(s(x)\big)$

With: k is the controller gain.

3.3.1 Speed control

In the sliding mode theory, we have:

(10) $\dot{S}_1 = -k_1\,sign(S_1)$

And we have (7): $S_1(\Omega) = \Omega_{ref} - \Omega$, so:

(11) $\dot{S}_1(\Omega) = \dot{\Omega}_{ref} - \dot{\Omega}$

By substituting the value of $\dot{\Omega}$ in equation (11) we obtain:

$$(12)\quad \begin{cases} \dot{S}_1(\Omega) = \dot{\Omega}_{ref} - \frac{1}{J}\left(p\left[(L_d - L_q)I_d\,I_q + \emptyset_f I_q\right] - C_r - f\Omega\right) \\ \dot{S}_1(\Omega) = \dot{\Omega}_{ref} - \left[\frac{p}{J}(L_d - L_q)I_d + \frac{p}{J}\emptyset_f\right]I_q + \frac{1}{J}C_r + \frac{f}{J}\Omega \end{cases}$$

By the equality of the equation (12) and (10) we obtain:

$$(13)\quad \dot{\Omega}_{ref} - \left[\frac{p}{J}(L_d - L_q)I_d + \frac{p}{J}\emptyset_f\right]I_q + \frac{1}{J}C_r + \frac{f}{J}\Omega = -k_1\,sign(S_1)$$

Then the speed control law is:

$$(14)\quad I_q = \dot{\Omega}_{ref} + \frac{1}{J}C_r + \frac{f}{J}\Omega + k_1\,sign(S_1) \times \frac{1}{\frac{p}{J}(L_d - L_q)I_d + \frac{p}{J}\emptyset_f}$$

3.3.2 Current control I_q

In the sliding mode theory, we have:

(15) $\dot{S}_2 = -k_2\,sign(S_2)$

And we have: $S_2(I_q) = I_q^{ref} - I_q$, so:

(16) $\dot{S}_2(I_q) = \dot{I}_q^{ref} - \dot{I}_q$

By substituting the value of $\dot{I}_q$ in equation (16) we obtain:

$$(17)\quad \begin{cases} \dot{S}_2(I_q) = \dot{I}_q^{ref} - \frac{1}{L_q}\left(V_q - R_s I_q - \omega L_d I_d - \omega\emptyset_f\right) \\ \dot{S}_2(I_q) = \dot{I}_q^{ref} - \frac{1}{L_q}V_q + \frac{R_s}{L_q}I_q + \frac{L_d}{L_q}\omega I_d + \frac{\omega}{L_q}\emptyset_f \end{cases}$$

By the equality of (17) and (15) we obtain:

$$(18)\quad \dot{I}_q^{ref} - \frac{1}{L_q}V_q + \frac{R_s}{L_q}I_q + \frac{L_d}{L_q}\omega I_d + \frac{\omega}{L_q}\emptyset_f = -k_2\,sign(S_2)$$

Then the current control law I_q is:

$$(19)\quad V_q = L_q\left[\dot{I}_q^{ref} + \frac{R_s}{L_q}I_q + \frac{L_d}{L_q}\omega I_d + \frac{\omega}{L_q}\emptyset_f + k_2\,sign(S_2)\right]$$

3.3.2 Current control I_d

In the sliding mode theory, we have:

(20) $\dot{S}_3 = -k_3\,sign(S_3)$

And we have: $S_3(I_d) = I_d^{ref} - I_d$, so:

(21) $\dot{S}_3(I_d) = \dot{I}_d^{ref} - \dot{I}_d$

By substituting the value of $\dot{I}_d$ in equation (21) we obtain:

$$(22)\quad \begin{cases} \dot{S}_3(I_d) = \dot{I}_d^{ref} - \frac{1}{L_d}\left(V_d - R_s I_d + \omega L_q I_q\right) \\ \dot{S}_3(I_d) = \dot{I}_d^{ref} - \frac{1}{L_d}V_d + \frac{R_s}{L_d}I_d - \frac{L_q}{L_d}\,\omega I_q \end{cases}$$

By the equality of (22) and (20) we obtain:

$$(23)\quad \dot{I}_d^{ref} - \frac{1}{L_d}V_d + \frac{R_s}{L_d}I_d - \frac{L_q}{L_d}\,\omega I_q = -k_3\,sign(S_3)$$

Then the current control law I_d is:

$$(24)\quad V_d = L_d\left[\dot{I}_d^{ref} + \frac{R_s}{L_d}I_d - \frac{L_q}{L_d}\,\omega I_q + k_3\,sign(S_3)\right]$$

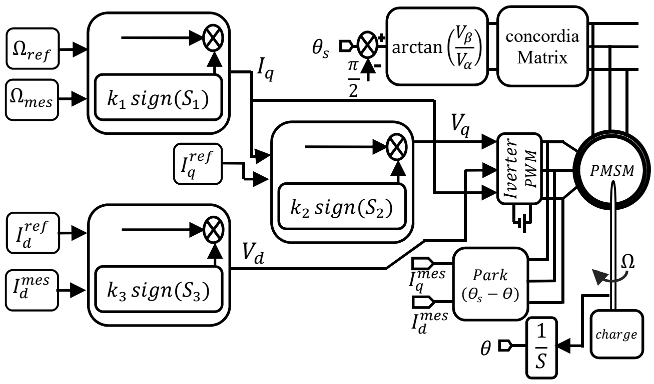

Fig.3. Block diagram of sliding mode control.

3.4 Simulation Results

The figures below show the performance of the sliding mode control applied to the PMSM. This test is carried out under the following conditions: the machine powered for driven at a reference speed equal to 157 Rad/s with a load applied equal to $C_r = 6N.m$ at time $t = 0.5s$.

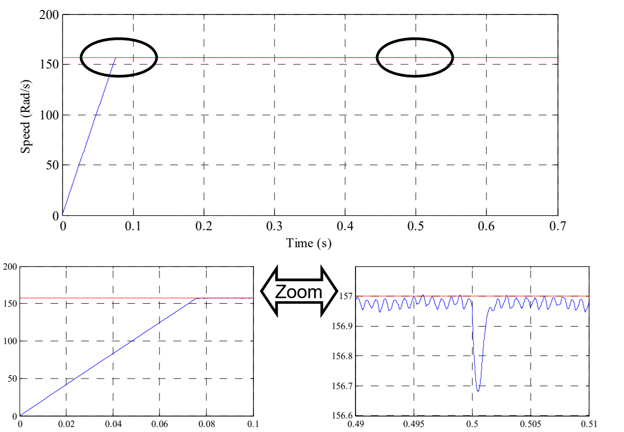

Fig.4. Numerical simulation results of the speed by the sliding control.

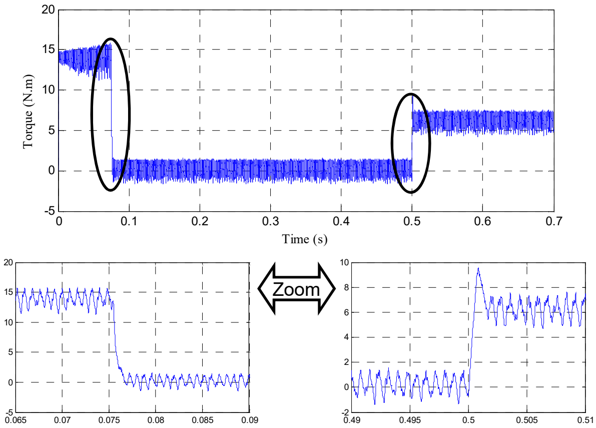

Fig.5. Numerical simulation results of the torque by the sliding control.

According to the results obtained in Figures 4 and 5 we notice that:

– A gradual increase in speed to reach its reference value without exceeding it.
– For the application of C_r at time $t = 0.5s$ the speed presents a decrease in speed and a rapid regain without exceeding the speed of its reference
– The torque in a note that undergoes a peak at the first moment of starting, then reaches the value of the resisting torque before and after the application of the load.

4. Hybrid type-1 fuzzy sliding mode control

The most significant disadvantage of sliding mode control is the high switching frequency (chattering). This phenomena is undesirable because it has the potential to stimulate unmodeled high-frequency modes within the regulated system [12].

To address this issue, a control that can forecast performance even when the system model is unknown is required. Variations in parameters or external disturbances must be accommodated by this control. These methods of control are commonly referred to as “intelligent control”, and they are based on fuzzy logic and genetic algorithms.

4.1 Principle of fuzzy logic

In traditional set theory, an element can only belong to a set if it is either zero or one, hence the degree to which an element belongs to a set can only be zero or one. In the theory of fuzzy sets, on the other hand, an element can more or less belong to a set, and the degree of membership of an element to a fuzzy set can take any value between 0 and 1 [24].

4.2 Structure of a fuzzy controller

Unlike conventional tuning techniques, fuzzy logic tuning does not use specific or precise formulas or mathematical relationships. But, it manipulates inferences with several fuzzy rules based [25]. A principal fuzzy logic regulator is presented in figure 6.

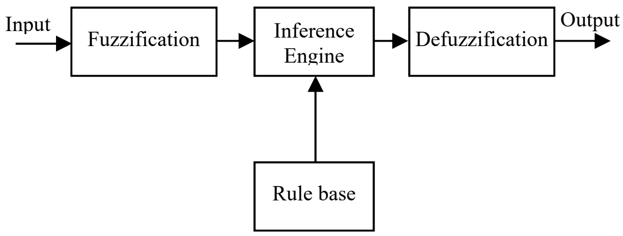

Fig.6. Basic components of a fuzzy controller [25].

4.3 Development of a fuzzy regulator for the PMSM

To provide strong high-performance regulation, the active and reactive power regulators are replaced with a sliding-fuzzy mode regulator in the following. This control (FSMC), figure (7), contains an equivalent control component (SMC) and a fuzzy control part (FLC), as proposed by the equation:

$$(25)\quad u_{FSMC} = u_{eq} + u_f$$

Where: u_{eq} is the equivalent control which indicates the notion of the state trajectory along the sliding surface. u_f is the fuzzy control (attractive), is a constant, which is set to satisfy the robustness requirement the mathematical development of this control is given in the previous section.

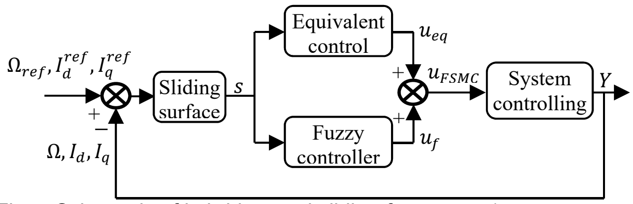

Fig.7. Schematic of hybrid control sliding-fuzzy type 1.

4.4 Knowledge base proposed

The triangle-shaped membership functions of error e and the derivative of error $\dot{e}$ are shown in Figures 8 and 9. The names NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big) are used to identify the fuzzy sets.

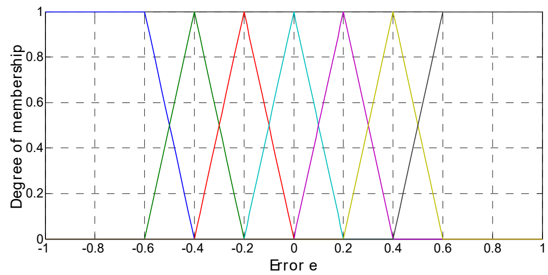

Fig.8. Membership functions for error e.

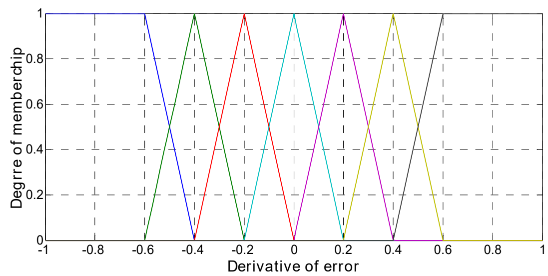

Fig.9. Membership functions for derivative of derivative error $\dot{e}$.

Figure 10 and 11 shows respectively the proposed membership functions for output variable and the surface of type-1 fuzzy control.

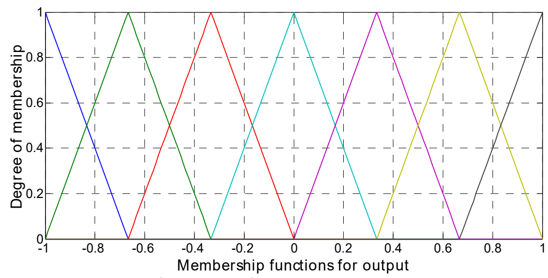

Fig.10. Membership functions for output u.

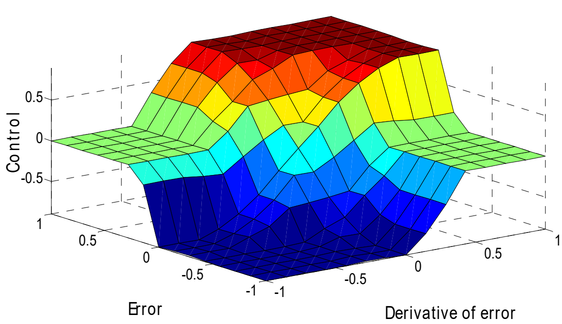

Fig.11. Surface of fuzzy controller.

The triangle membership function, max-min reasoning, and center of gravity defuzzification methods are employed in this study since they are the most commonly used approaches in [25].

Because signals near the origin (stationary state) require more precision, all membership functions (MFs) are asymmetrical. For the e and $\dot{e}$ signals, seven MFs were chosen. For both positive and negative values of the variables, all MFs are symmetrical. As a result, a maximum of 7x7 = 49 rules can be constructed, as shown in Table 1.

Table 1. Linguistic Rule Table.

Control		$e(t)$						
		NB	NM	NS	ZE	PS	PM	PB
$\dot{e}(t)$	NB	NB	NB	NB	NB	ZE	ZE	ZE
	NM	NB	NB	NM	NM	ZE	ZE	ZE
	NS	NB	NB	NS	NS	PS	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	NS	PS	PS	PB	PB
	PM	ZE	ZE	ZE	PM	PM	PB	PB
	PB	ZE	ZE	ZE	PB	PB	PB	PB

The suggested sliding-fuzzy type-1 control of the PMSM is shown in block diagram form in Figure 12, we used the same sliding mode control structure with a change of the "$sign$" functions by type 1 fuzzy regulators.

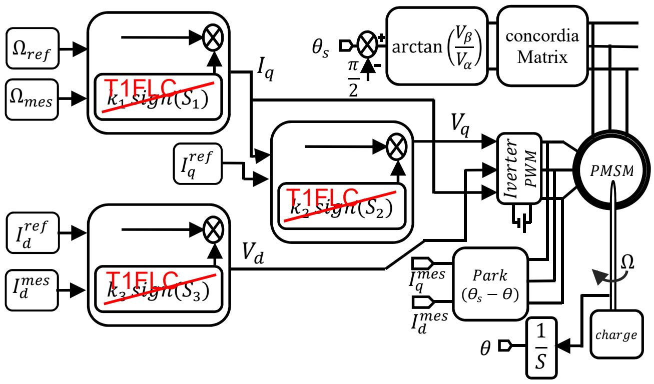

Fig.12. Type-1 fuzzy sliding mode control block diagram.

4.5 Simulation Results

This step's goal is to use a hybrid sliding-fuzzy control system to operate the permanent magnet synchronous machine. Figures 13 and 14 show the machine speed and torque simulation results. This test is carried out under the same previous conditions, i.e. the machine is powered by a voltage which gives a reference speed equal to 157 Rad/s with a load applied equal to $C_r = 6N.m$ (step of resistance torque) at time $t = 0.5s$.

The application of this control strategy begins with the determination of the relative degree of the variation to be regulated (Ω, I_d and I_q). The output quantities represent the current references and the control voltages applied to the machine.

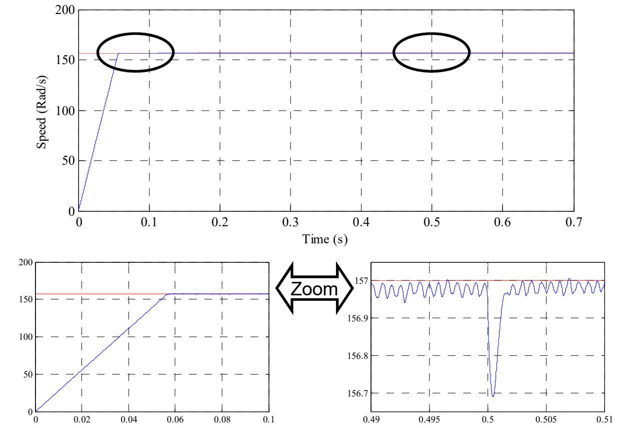

Fig.13. Numerical simulation results of the speed by the type-1 fuzzy sliding control.

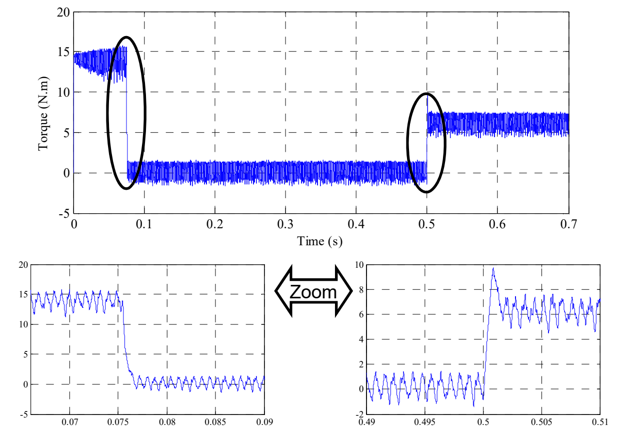

Fig.14. Numerical simulation results of the torque by the type-1 fuzzy sliding control.

The simulation results show the improvement of the hybrid sliding type-1 fuzzy control in the face of the variation of the resistance torque of the machine compared to the control by sliding mode. We also notice:

- The shape of the speed follows its reference without exceeding the latter during the transient state and after application of the load;
- At the instant of the application of resistive torque C_r of $t = 0.5s$, a decrease in speed and rapid recovery without exceeding the speed of its reference;
- We note that the torque undergoes a peak at the first moment of starting, then reaches the value of the resisting torque before and after the application of the load.

5. Control of hybrid type-2 fuzzy sliding mode

To apply this control to our system, we used the same type-1 fuzzy sliding control structure with a change of type-1 fuzzy regulators by type-2 fuzzy regulators.

5.1 Interval type-2 fuzzy logic system

A T2FS in the universal set X is designated as $\tilde{A}$, which is described by a type-2 membership function $\mu_{\tilde{A}}(x)$. A secondary membership function (MF) or secondary set, which is a type-1 set in [0, 1] [5, 12], can be referred to as such.

$$(26)\quad \tilde{A} = \int_{x\in X} \mu_{\tilde{A}}(x)/(x) = \int_{x\in X} \left[\int_{u\in J_x} f_x(u)/(u)\right]/(x)$$

Where: $f_x(u) = 1, \quad \forall u \in J_x \subseteq [0,1], \quad \forall x \in X$. Then the secondary MFs are interval sets such that $\mu_{\tilde{A}}(x)$ can be called an interval type-2 MF [26]. Therefore, T2FS $\tilde{A}$ can be rewritteh as:

(27) $\tilde{A} = \int_{x\in X} \mu_{\tilde{A}}(x)/(x) = \int_{x\in X} \left[\int_{u\in J_x} 1/(u)\right]/(x) \quad J_x \subseteq [0,1]$

The main structural difference between a T2FLS and a T1FLS [20] is that the output processing block in a T2FLS, which comprises of type-reduction and defuzzification, replaces the defuzzifier block of a T1FLC.

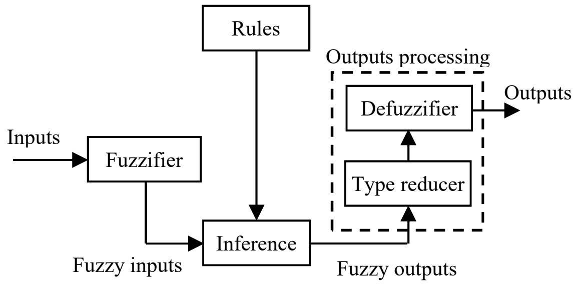

Fig.15. Structure of T2FLS [12].

Throughout this paper, we solely address singleton input fuzzification. The firing strength in (28) can be derived in the same way as T1FLS by using the firing strength F inference process:

(28) $F^i = \coprod_{x\in X}\left[\prod_{k=1}^{n} \mu_{\tilde{F}_k^i}(x_k)\right]$

Where: $\prod$ is the meet operation and $\coprod$ is the join operation [26].

The upper MF in Gaussian IT2FS, as illustrated in figure 15, is a subset with the highest membership grade, whereas the lower MF is a subset with the lowest membership grade. The join operation in (28) joins the results of meet operations with the highest value. An interval type-1 set [27] can be obtained as a result of the join operation:

(29) $F^i \equiv \left[\underline{f}^i, \bar{f}^i\right]$

With: $\underline{f}^i$ and $\bar{f}^i$ are given as:

(30) $\begin{aligned} \underline{f}^i &= \underline{\mu}_{F_1^i}(x_1) \times \ldots \times \underline{\mu}_{F_p^i}(x_n) \\ \bar{f}^i &= \overline{\mu}_{F_1^i}(x_1) \times \ldots \times \overline{\mu}_{F_n^i}(x_n) \end{aligned}$

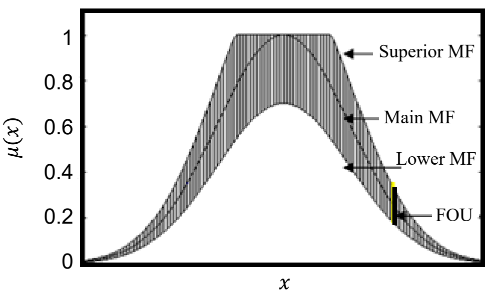

Fig.16. Interval type-2 Gaussian fuzzy set.

Type reduction proposed bay Karink and mendel [26, 28] using the centre of set method is expressed in (31):

(31)
$$y(x) = [y_l(x), y_r(x)] = \int_{y^1\in[y_l^1, y_r^1]} \cdots \int_{y^M\in[y_l^M, y_r^M]} \int_{f^1\in[\underline{f}^1, \bar{f}^1]} \cdots \int_{f^M\in[\underline{f}^M, \bar{f}^M]} \frac{1}{\frac{\sum_{i=1}^{M} f^i y^i}{\sum_{i=1}^{M} f^i}}$$

As a result, [28] can be used to express the left-most point y_l and the right-most point y_r.

(32) $\begin{cases} y_l(x) = \frac{\sum_{i=1}^{M} f_l^i y_l^i}{\sum_{i=1}^{M} f_l^i} \\ y_r(x) = \frac{\sum_{i=1}^{M} f_r^i y_r^i}{\sum_{i=1}^{M} f_r^i} \end{cases}$

The average of the defuzzified crisp output of an interval type-2 FLS is:

(33) $Y(x) = \frac{y_l(x) + y_r(x)}{2}$

5.2 Developing a fuzzy control system for a PMSM

The design of a new nonlinear drive for the permanent magnet synchronous machine is presented in this section. To improve its robustness, the proposed control is based on the sliding mode control technique and complemented with an interval type-2 fuzzy controller.

A significant flaw in control algorithms based on sliding mode techniques is the chattering effect, which is the high frequency oscillation of the controller output. An interval type-2 fuzzy system is utilized to approximate the hitting control term to address this difficulty and lessen the chattering phenomena. Figure 17 depicts the suggested type-2 fuzzy sliding mode control scheme's configuration.

(34) $u_{IT2FSMC} = u_{eq} + u_f$

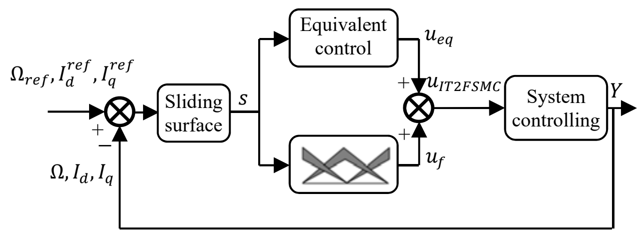

Fig.17. Schematic of hybrid control sliding- Interval type-2 fuzzy.

5.3 Interval type-2 fuzzy logic control proposed

The current error is the difference between the reference value and the measured value of currents, and the error derivative of the latter is the initial input of the fuzzy system. The fuzzy type-2 membership functions of the input error e and derivative error $\dot{e}$ are presented in Figure 18 and 19.

The entries are represented by five language labels: NB (Negative Big), N (Negative), Z (Zero), P (Positive), PB (Positive Big). The MFs for the inputs are selected as Gaussian for all labels.

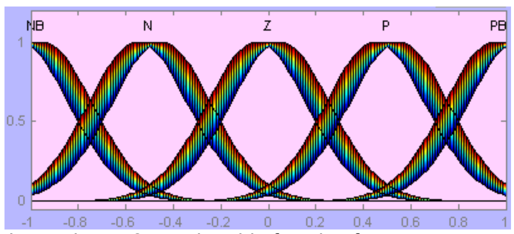

Fig.18. Interval type-2 membership function for error.

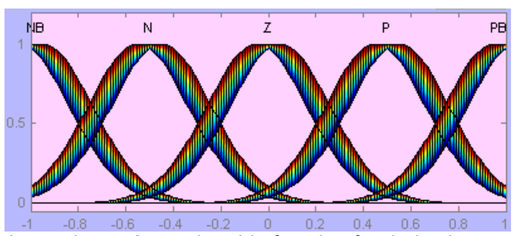

Fig.19. Interval type-2 membership function for derivative error.

We'll need 25 rules to cover all possible inputs if we have five values of error (e) and five values of change in error, derivative, ($\dot{e}$). These are frequently written as follows in a table:

Table 2. Fuzzy rules for type-2 FLCs.

Control		$e(t)$				
		NB	N	Z	P	PB
$\dot{e}(t)$	NB	NB	NB	N	N	Z
	N	NB	N	N	Z	P
	Z	N	N	Z	P	P
	P	N	Z	P	P	PB
	PB	Z	P	P	PB	PB

The membership functions of the output (u_f) discontinuous control is presented in the figure 20.

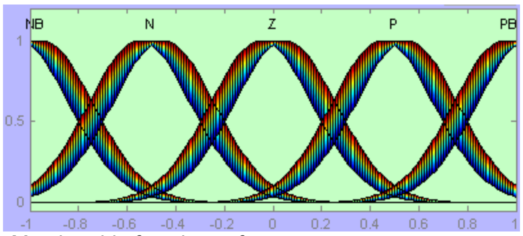

Fig.20. Membership functions of output.

The surface of the Interval type-2 fuzzy controller is shown in Figure 21.

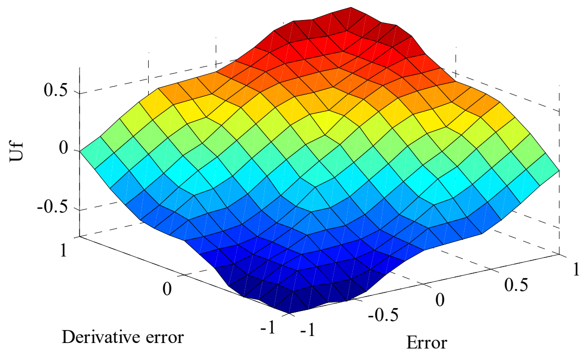

Fig.21. Surface of interval type-2 fuzzy.

5.4 Simulation Results

The figures below represent the simulation results of the machine controlled by a type-2 fuzzy sliding hybrid control under a nominal load (no load) then under load ($C_r = 6N.m$) at time $t = 0.5s$. The powered machine is driven at a reference speed equal to 157 Rad/s. The parameters of the permanent magnet synchronous machine used in this work are given in the Appendix.

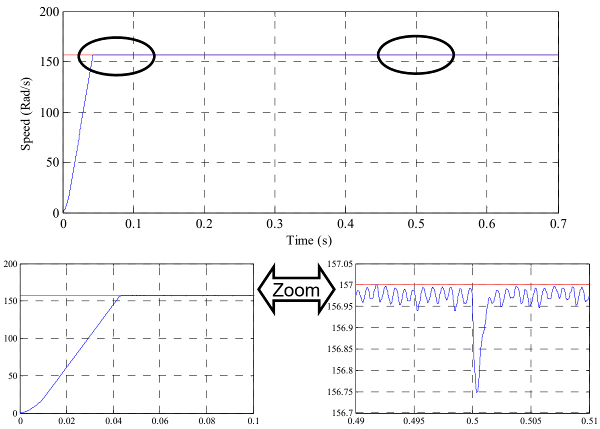

Fig.22. Numerical simulation results of the speed by the type-2 fuzzy sliding control.

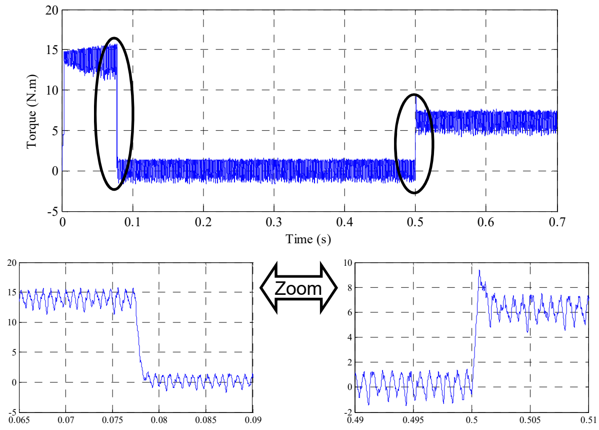

Fig.23. Numerical simulation results of the torque by the type-2 fuzzy sliding control.

The observation of the simulation results obtained in figures 22 and 23 shows that the same remarks represented by the two previous commands, but with a remarkable improvement also than the results already obtained by the two previous commands. We can note from the torque curve that the oscillations (chattering) are reduced and we can also notice:

- The speed curve follow their new references during after the transient state and after the application of the load;
- At the instant of the application of resistive torque C_r of $t = 0.5s$, a decrease in speed and a rapid return to its reference;
- The torque reaches the value of the resisting torque before and after the application of the load.

6. Comparative study

We will give a comparative study of the different control laws established and synthesized for the permanent magnet synchronous machine in this work to investigate the different control laws developed and synthesized for it. The experiment was repeated under the same conditions.

The goal of this section is to compare and contrast the various commands that we've covered so far. This comparison is based on a series of experiments performed throughout the system's transitory and permanent operation.

6.1 Qualitative comparison

This comparison is based on the observation of speed simulation results obtained by applying various control strategies to the PMSM. In this comparison, we carried out the test which based on the application of a load ($C_r = 6N.m$) as a step at time $t = 0.5s$ and the machine rotates at a fixed speed (+157 Rad/s).

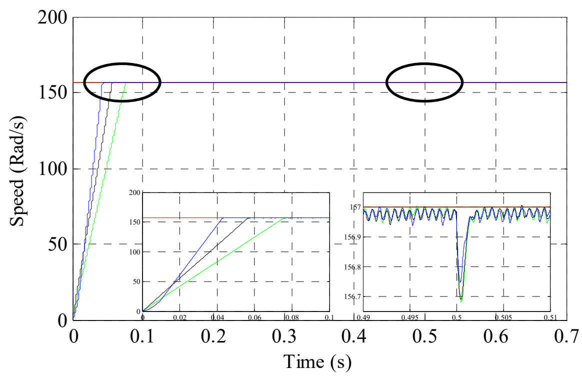

Fig.24. Numerical simulation results of the speed by the different control techniques (sliding control (—), type-1 fuzzy sliding (—) and type-2 fuzzy sliding (—)).

The simulation results show that the speed follows their reference in the three types of controls, however the response time and the overshoot. We note that the best values of the latter are the values obtained during the application of type-2 fuzzy logic.

6.2 Quantitative comparison

The second comparison includes four criteria to evaluate the existing difference between the actual speed response and the ideal step-type response (the set value), we can calculate the integral of a positive term involving the error. An index calculated in this way takes on a value all the higher as the actual response is far from the ideal response. In practice, the integral is calculated over an interval [0, T] large enough to contain the entire transient state.

- The integral of the absolute value of the error $e(t)$ is given by:

(37) $IAE = \int_0^T |e(t)|dt$

- The integral of the quadratic error:

(38) $ISE = \int_0^T e^2(t)dt$

- To penalize the system whose transient state lasts too long, we also use the integral of the product of the error of time, given by:

(39) $ITAE = \int_0^T t|e(t)|dt$

- And also the integral of the product of the quadratic error of time, given by:

(40) $ITSE = \int_0^T t.e^2(t)dt$

For quantitative comparison between different control techniques. The ISE, IAE, ITSE, and ITAE values of the simulation results employing sliding mode control, sliding fuzzy type-1, and sliding fuzzy type-2 are shown in Table.3. When comparing the fuzzy type-2 controller to the other approaches, it can be shown that the fuzzy type-2 controller performs better. Actually, with a sampling period of h=10-4, these performance indices are produced at the end of the simulation time (T = 0.7sec).

Table 3. IAE, ISE, ITAE and ITSE performance indexes.

Controllers / Index	Sliding mode control	Sliding fuzzy type-1	Sliding fuzzy type-2
IAE	5.9670	4.4866	3.7879
ISE	623.6154	470.2371	434.6425
ITAE	0.1559	0.0901	0.0606
ITSE	11.7945	6.6593	4.8911

6.3 Robustness comparison

The final comparison is based on a robustness test of the suggested controls, which includes an examination of the impact of PMSM parametric fluctuations on their performance. Knowing that in a real system, these characteristics can change due to a variety of physical factors (saturation of the inductors, heating of the resistances, ..., etc.).

In this case, the stator resistance variation test (R_s) of 100% of its nominal value was performed at time $t = 0.3s$ and at time $t = 0.5s$ a variation of the value load ($C_r = 6N.m$). Fig. 25 represent the speed curve to have the robustness of the synthesized controls. According to these results, we visualized that the hybrid sliding type-2 fuzzy control has a strong robustness and ensures good performance.

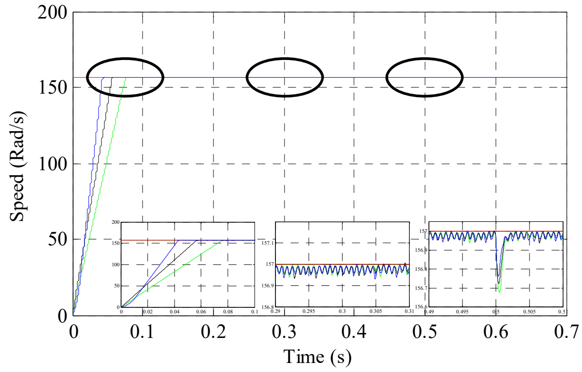

Fig.25. Numerical simulation results of the speed during the variation of the stator resistance by the different control techniques (SMC (green)), T1FSMC (black) and IT2FSMC (blue)).

7. Conclusion

In this paper, we compared the efficiency and performance of three controls: sliding mode control, hybrid sliding type-1 fuzzy logic, and hybrid sliding type-2 fuzzy logic, all of which were applied to the Permanent Magnet Synchronous Machine to represent the efficiency and performance of each in the presence and absence of parametric and external variations. This research is focused on three key criteria: quality, quantity, and robustness in both temporary and permanent operations.

In the presence and absence of parametric and external changes, the results reveal that hybrid sliding type-2 fuzzy logic control is the most efficient and effective control over our system compared to sliding mode control and hybrid sliding type-1 fuzzy logic control.

The hybrid control, which combines sliding mode control and type 2 fuzzy artificial intelligence, alleviates chattering and reduces the control supplying organ's strong oscillations.

Appendix

Table.4. Simulation parameters of the PMSM.

Parameters	Value	Parameters	Value
R_s	0.12 Ω	L_d	0.0014 H
$\emptyset_f$	0.12 Wb	Ω	157 rad/s
P	4	L_q	0.0028 H
f	0.0014	J	0.0011 $Kg.m^2$

***Authors**: Dr. Abdelghafour HERIZI, Dr. Riyadh ROUABHI, Dr. Abderrahim ZEMMIT, Electrical Engineering Department, Faculty of Technology, University Mohamed Boudiaf of M'sila, BP 166 Ichbilia 28000, Algeria, E-mail: abdelghafour.herizi@univ-msila.dz*

REFERENCES

[1] Hoyos F.E., Candelo-Becerra J.E., Hoyos Velasco C.I., Application of Zero Average Dynamics and Fixed Point Induction Control Techniques to Control the Speed of a DC Motor with a Buck Converter, *Applied Sciences*, 10 (2020), No. 5, 1-13.

[2] Pyrhonen J., Hrabovcova V., Semken R.S., Electrical machine drives control: an introduction, *John Wiley & Sons Ltd*, First edition, 2016.

[3] Djerioui A., Houari A., Ait-Ahmed M., Benkhoris M.F., Chouder A., Machmoum M., Grey Wolf based control for speed ripple reduction at low speed operation of PMSM drives, *ISA transactions,* 74 (2018), 111-119.

[4] Qiao W., Tang X., Zheng S., Xie Y., Song B., Adaptive two-degree-of-freedom PI for speed control of permanent magnet synchronous motor based on fractional order GPC, *ISA Transactions,* 34 (2016), 303-313.

[5] Rouabhi R., Abdessemed R., Herizi A., Boudia M., Comparative Study Between Two Control Techniques Applied on the Permanent Magnet Synchronous Machine (PMSM),

Advances in Modelling and Analysis C, 74 (2019), No. 2-4, 51-58.
[6] Houari A., Bouabdallah A., Djerioui, A., Machmoum M., Auger F., Darkawi A., Olivier J., Benkhoris M.F., An effective compensation technique for speed smoothness at low speed operation of PMSM drives, *IEEE Trans on Industry Applications*, 54 (2018), No. 1, 647-655.
[7] Wu L.H., Liu Z.H., Li X.H., GPU-accelerated parallel coevolutionary algorithm for parameters identification and temperature monitoring in permanent magnet synchronous machines, *IEEE Transactions on Industrial Informatics*, 11 (2015), No. 5, 1220-1230.
[8] Robyns B., Fu y., Labrique F., Buyse H., Commande numérique de moteurs synchrones à aimants permanents de faible puissance, *Journal de physique III,* 5 (1995), No. 8, 1255-1268.
[9] Sturtzer Guy., Smigiel E., Modélisation et Commande des Moteurs Triphasés, Commande vectorielle des moteurs synchrones, commande numérique par contrôleurs DSP, *Edition Ellipses,* 2000.
[10] Do-Kwan H., Wook H., Ji-Young L., Byung-Chul W., Design, Analysis, and Experimental Validation of a Permanent Magnet Synchronous Motor for Articulated Robot Applications. *IEEE Transactions on Magnetics,* 54 (2018), No. 3, 1-4.
[11] Ayedi D., Boujelben M., Rekik C., Hybrid Type-2 Fuzzy-Sliding Mode Controller for Navigation of Mobile Robot in an Environment Containing a Dynamic Target, *Journal of Robotics,* (2018), 1-10.
[12] Zouggar E., Chaouch S., Ould Abdeslam D., Abdelhamid L., Sliding Control with Fuzzy Type-2 Controller of Wind Energy System Based on Doubly Fed Induction Generator, *Instrumentation Mesure Metrologie,* 18 (2019), No. 2, 137-146.
[13] Nasri A., Hazzab A., Bousserhane I.K., Hadjiri S., Sicard P., Two wheel speed robust sliding mode control for electrical vehicle drive, *Serbian Journal of Electrical Engineering,* 5 (2008), No. 2, 199-216.
[14] Shim H.S., Kim J.H., Koh K., Variable structure control of non holonomic mobile robots, *IEEE conf. Robot. Automat,* (1995), 1694-1699.
[15] Hamdi Pacha F.Z., Amri W., Fezai N., Benamor A., Intelligent control based on adaptative fuzzy logic for permanent magnet synchronous machine, *4th International Conference on Advanced Systems and Emergent Technologies (IC ASET),* Tunisia, 2020.
[16] Zemmit A., Messalti S., Harrag A., A new improved DTC of doubly fed induction machine using GA-based PI controller, *Ain Shams Engineering Journal,* 9 (2018), No. 4, 1877-1885.
[17] Lowen R., Verschoren A., Foundations of generic optimization, Volume 2: applications of fuzzy control, genetic algorithms and neural networks, *Springer,* 2008.
[18] Ben Attous D., Bekakra Y., Speed control of a doubly fed induction motor using fuzzy logic techniques, *International Journal on Electrical Engineering and Informatics,* 2 (2010), No. 3, 179-191.
[19] Hamdi Pacha F.Z., Herizi A., Amri W., Benamor A., Design and Diagnosis of current faults in electrical power systems of permanant magnet synchrones machine, *5th International Conference on Advanced Systems and Emergent Technologies (IC ASET),* Tunisia, 2022.
[20] Labrique F., Séguier G., Bausiere R., Les convertisseurs de l'électronique de puissance. Volume 4: la conversion continu-alternatif, *Lavoisier,* 1995
[21] Bousserhane I.K., Boucheta A., Hazzab A., Mazari B., Rahli M., Fellah M.K., Fuzzy-Sliding Controller Design for Single Sided Linear Induction Motor Position Control, *The International Conference on Computer as a Tool,* (2007), 1942-1947.
[22] Slotine W., Li J.J.E., Applied nonlinear control, *Prence Hall,* USA, 1998.
[23] Lopez P., Nouri A.S., Théorie Elémentaire Et Pratique de La Commande Par Les Régimes Glissants, *Springer,* 2006.
[24] Zadeh L., The Concept of a Linguistic Variable and its Application to Approximate Reasoning, *Information Sciences,* 8 (1975), 199-249.
[25] Herizi A., Smaini H.E., Mahmoudi R., Bouguerra A., Zeghlache S., Rouabhi R., Comparison Study Between Mamdani and Sugeno Fuzzy Inference Systems for Speed Control of a Doubly-Fed Induction Motor, *8ème Conférence Internationale en Automatique & Traitement de Signal,* Sousse, Tunisie, 2019.
[26] Liang Q., Mendel J.M., Interval type-2 fuzzy logic systems: theory and design, *IEEE Transactions on Fuzzy Systems,* 8 (2000), No. 5, 535-550.
[27] Mendel J.M., John R.I., Liu F., Interval type-2 fuzzy logic systems made simple, *IEEE Transactions on Fuzzy Systems,* 14 (2006), No. 6, 808-818.
[28] Mendel J.M, Uncertain rule-based fuzzy logic systems: introduction and new directions, *Prentice-Hall,* 2001.