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1

Intelligent monitoring of PMSM based on adaptive fuzzy logic for diagnosis

Abstract. In this paper, the fuzzy adaptive gain monitoring method (AGFLC) uses direct field-oriented control (DFOC) to monitor the speed of permanent magnet synchronous motors (PMSM). This surveillance strategy can detect the error of the velocity parameter, forcing the monitored system to achieve the desired reference model, and eliminating the velocity error. First, we examine the mathematical model describing the internal behavior of PMSM to design our system based on the priory physical model of the system. Then, we propose an intelligent method that combines a fuzzy control algorithm with its related control rules, aiming to monitor the speed of PMSM. This problem is solved by combining the two parameters of error and its variation. A fuzzy algorithm has proven to be an effective method to adjust the speed by suppressing disturbances. Furthermore, an adapted gain fuzzy controller, which provides a fast dynamic response without overshooting at various dynamic actions, has been suggested to compensate for all external disturbances. The obtained simulation results demonstrate the efficiency of the monitoring method for fault detection and localization and verify the performance of the adaptive algorithm control system.

Streszczenie. W tym artykule, rozmyta adaptacyjna metoda monitorowania wzmocnienia (AGFLC) wykorzystuje bezpośrednie sterowanie zorientowane na pole (DFOC) do monitorowania prędkości silników synchronicznych z magnesami trwałymi (PMSM). Ta strategia nadzoru może wykryć błąd parametru prędkości, zmuszając monitorowany system do osiągnięcia pożądanego modelu odniesienia i eliminując błąd prędkości. Najpierw badamy model matematyczny opisujący wewnętrzne zachowanie PMSM, aby zaprojektować nasz system w oparciu o priorytyczny model fizyczny systemu. Następnie proponujemy inteligentną metodę, która łączy algorytm kontroli rozmytej z powiązanymi z nim regułami kontroli, mającymi na celu monitorowanie prędkości PMSM. Problem ten jest rozwiązywany poprzez połączenie dwóch parametrów błędu i jego zmienności. Algorytm rozmyty okazał się być skuteczną metodą regulacji prędkości poprzez tłumienie zakłóceń. Ponadto do kompensacji wszystkich zakłóceń zewnętrznych zaproponowano regulator rozmyty o dostosowanym wzmocnieniu, który zapewnia szybką odpowiedź dynamiczną bez przekroczeń przy różnych akcjach dynamicznych. Uzyskane wyniki symulacji pokazują skuteczność metody monitorowania do wykrywania i lokalizacji uszkodzeń oraz weryfikują wydajność systemu sterowania z algorytmem adaptacyjnym. (Inteligentne monitorowanie PMSM w oparciu o adaptacyjną logikę rozmytą do celów diagnostycznych)

Keywords: Permanent Magnet Synchronous Machine, Diagnosis, Vector control, Fuzzy controller, Adaptive gain, Speed Control.
Słowa kluczowe: Maszyna synchroniczna z magnesami trwałymi, diagnostyka, sterowanie wektorowe, sterowanie rozmyte.

1. Introduction

Permanent Magnet Synchronous Machines (PMSM) are increasingly used in the industry thanks to their high performances of low inertia, high mass torque, and reduced maintenance. In the field of variable speed drives, several actuators combining Alternative Current (AC) machines and static converters offer new perspectives. Variable speed drives with high dynamic performances, such as good steady-state accuracy, high overload capability over the entire speed range, and robustness to various disturbances [1].

An external system's application of decoupled controls aims to obtain good performance [2]. It consists of separating the controls of the flow from the torque by the vector control method as it has been developed in [5]. The loss of stability of the traditional controllers considered is generally caused by internal and external parameters [3, 4]. Using a fixed parameter control impacts the control system's output. So, both stabilization and trajectory monitoring methods benefit from using robust control algorithms as it is worked in [6]. Adaptive fuzzy logic control (AFLC) is a new ambiguous nonlinear system based on developed algorithms' control laws. The suggested adaptive gain fuzzy controller compensates for the effects of external disturbances. In our work, a new approach has been proposed to improve the control performance of the Permanent Magnet Synchronous Machine fed by a hysteresis current-controlled voltage inverter with direct flux orientation. This approach is based on intelligent control using fuzzy logic techniques.

This approach is based on intelligent control using fuzzy logic techniques. The main contribution of the present study is the design and the synthesis of a robust controller that guarantees a stable and fast dynamic speed under all operating conditions, and a total rejection of external disturbances. The application of adaptive gain fuzzy use avoids a heavy computational burden; its better performance than the traditional PI control. This paper aims to introduce an adaptive gain fuzzy logic control AGFLC approach for speed diagnosis PMSM.

The structure of this work is as follows. A design model that describes the internal behavior of the system identifies the system in section 2. Introduces parametric estimation method with an overview of the inverter in section 3. Vector control using direct flow orientation is discussed in Section 4. Section 5 explains fuzzy logic principles and techniques for monitoring PMSM speed using smart methods (FLC) and (AGFL). Simulation results and discussions are analyzed in Section 6.

2. Permanent magnet synchronous motor design

To simplify the modeling of the system [6] the electrical equations of the stator and rotor of a static magnet synchronous machine without a damper within the park reference are written as follows.

2.1 Electrical equations

(1) $V_d = R_s i_d + \frac{d\varphi_d}{dt} - \omega_r \varphi_q$

(2) $V_q = R_s i_q + \frac{d\varphi_q}{dt} + \omega_r \varphi_d$

2.2 Magnet equations

(3) $\varphi_d = L_d i_d + \varphi_f$
(4) $\varphi_q = L_q i_q$
(5) $V_f = R_f i_f + \frac{d\varphi_f}{dt}$

2.3 Mechanical equations

(6) $J\frac{d\Omega_r}{dt} = C_e - C_r - f_c \Omega$

The expression of the electromagnetic torque as a function of the currents is as below:

(7) $C_e = \frac{3}{2}p[(L_d - L_q)i_d i_q + i_q \varphi_f]$

where: R_s resistance of each stator phase, R_f the rotor resistance, V_f The rotor voltage, C_e The electromagnetic couple; J The moment of inertia of the rotating machine; p the number of pairs of poles; Ω_r The speed of rotation of the machine; ω_r The electrical speed of the rotor; f_c the coefficient of friction.

3. Parametric estimation approach

This approach supposes the expression of a mathematical model which describes the system's internal behavior. It involves estimating the physical or structural parameters contained in this model from measurements of real inputs and outputs of the system. To detect and identify the occurrence of a failure, a comparison is carried out between its estimated values and the normal state reference values [5, 7].

3.1 Auto-piloted synchronous machine

The autopilot system consists in imposing on the machine's supply currents a frequency strictly linked to the rotor frequency. The synchronous machine operates according to a principle similar to that of the Direct Current (DC) machine. Switching is no longer performed by the passage of brushes, but by semi-conductors. While the frequency control is achieved by a control circuit of its semiconductors, from a signal of the rotor position or the phase of the machine voltage.

This solution eliminates any risk of motor breakdown; any slow or abrupt speed reduction, any slow or sudden slowing down of the speed automatically leads to a corresponding decrease in the frequency of the supply currents. In figure 1 the structure of the autopilot control of the permanent magnet synchronous machine represents.
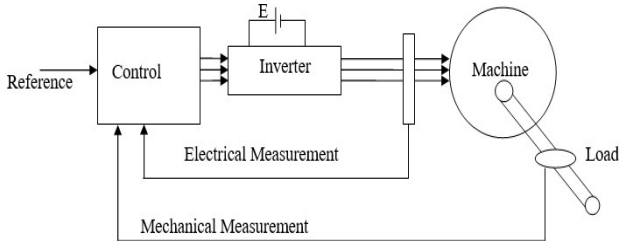

Fig.1. Structure of a controlled machine.

3.2 Modeling of the voltage inverter

The simple inverter voltages in the matrix form are shown below:

$$(8) \begin{cases} U_{ab} = V_a - V_b = E(F_1 - F_2) \\ U_{bc} = V_b - V_c = E(F_2 - F_3) \\ U_{ca} = V_c - V_a = E(F_3 - F_1) \end{cases}$$
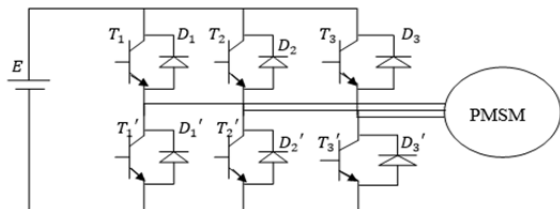

Fig.2. Diagram of a voltage inverter.

We define the logic functions as follows:
- $F_j = 1$ if T_i is closed and T'_i open
- $F_j = 0$ if T'_i closed et T_i open

Figure 2 shows a schematic of an inverter, which consists of six transistors ($T_1, T_2, T_3, T'_1, T'_2, T'_3$) shunted in antiparallel by recuperation diodes ($D_1, D_2, D_3, D'_1, D'_2, D'_3$).

Which semiconductors of the inverter are considered idealized components [7, 8].

4. Vector control approach

The principle of a vector control method in the permanent magnet syhcrones machine is to orient the current vector and the flux vector to make the synchronous machine behavior like that of a split-excitation DC machine where the field current monitors the flux and the field current monitors the torque [9, 10].

The electromagnetic torque of the DC machine is written [11, 14].

$$(9) \quad C_e = \frac{3}{2} p(\varphi_d i_q - \varphi_q i_d)$$

If we impose i_d as a zero component, the iq component becomes the only one that controls the torque. The shape of the electromagnetic torque will therefore be:

$$(10) \quad C_e = \frac{3}{2} p\varphi_f i_q = k_t i_q$$

Vector control is typically applied to voltage-fed, current-regulated machines on the d and q axes. This topology allows for more dynamic torque control while eliminating the disadvantage of a current supply [12, 15]. To control the torque of a static magnet synchronous machine, it is necessary to control the current vector [13,17].

The conventional speed controller (PI) in the investigated control is calculated from the linear model given in the diagram in Fig 3. We use one of the classical techniques developed for linear systems to synthesize it [6,19].
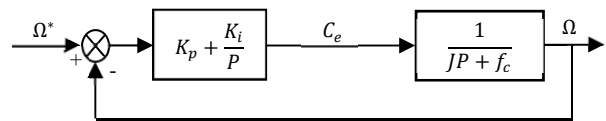

Fig.3. Speed control loop diagram.

The transfer function of the PI controller is given as follows [16,18] :

$$(11) \quad F(p) = k_p + \frac{k_i}{P}$$

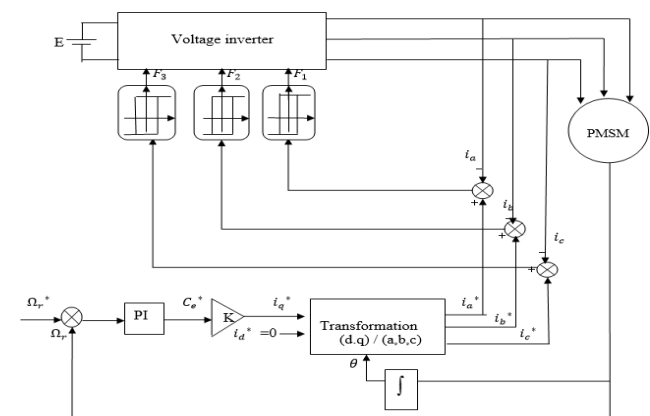Figure 4 shows an illustration of the vector control method.

Fig.4. Vector control of the PMSM powered with a voltage inverter.

5. AGFLC strategy

The fuzzy logic theory has become a very active research area, applied to complex systems, mathematically defined systems, and physical phenomena with exact mathematical models. This theory is based on the linguistic approach and decision-making. Fuzzy control is based on the knowledge of the operator who has a control strategy

formed by a set of decision rules whose form depends on the process to be controlled.

Thus, the envisaged controller requires an algorithm allowing the conversion of the linguistic control strategy based on the knowledge of an expert into an MSAP control strategy [20, 21].

The appropriate selection of process state variables and control variables is essential to characterize a fuzzy system. In addition, the selection of language variables has a significant effect on the performance of a fuzzy controller. During this selection step, the engineer's experience and knowledge play an important role. In particular, the choice of linguistic variables and their membership functions has a great influence on the fuzzy controller structure. Typically, in a fuzzy controller, the linguistic variables are the error e_k, the variation of this error Δe_k, and the variation of the order Δu_k. Practically, the database contains the membership functions of the linguistic variables representing e_k, Δe_k and Δu_k. We have limited the universes of the discourse of the error e_k and the variation of the error Δe_k at the interval [−1, 1], and we have limited the variation of the order Δu_k at the interval [11, 20]. The triangular and trapezoidal membership functions, the max-min reasoning method, and the defuzzification method are all included in this paper because they have been widely cited in the literature [12, 21].

This controller is built around a decision organ manipulating subjective and imprecise rules like those of the common language applied to the system and can control it [22, 28]. These rules Obtaining from experts who know the system well [23, 24].

The problem of the variation of the parameters, which has consequences on the performance of the system and can even lead to instability of the system, can be solved by an adaptive fuzzy control approach. Where the controller adapts to the operating conditions of the system. We have proposed a rule matrix that has two entries, the error, and its variation, based on the following two principles:

- If the output to be adjusted is equal to the desired value and the variation of the error is zero, the control will be kept constant.
- If the output to be adjusted deviates from the desired value, the action will depend on the sign and value of the error and its variation.

A fuzzy controller can be seen as an expert system operating from a knowledge representation based on the theory of fuzzy sets. The process knowledge base is composed of all the information we have on the process, it allows us to define the membership functions and the fuzzy rules of the fuzzy controller.

5.1 Database

The appropriate selection of process state variables and control variables is essential to characterize a fuzzy system. In addition, the selection of language variables has a significant effect on the performance of a fuzzy controller. During this selection step, the engineer's experience and knowledge play an important role. In particular, the choice of linguistic variables and their membership functions has a great influence on the fuzzy controller structure [25, 27]. Typically, in a fuzzy controller, the linguistic variables are the error e_k, the variation of this error Δe_k, and the variation of the order Δu_k. Practically, the database contains the membership functions of the linguistic variables representing e_k, Δe_k and Δu_k. We have limited the universes of the discourse of the error e_k and the variation of the error Δe_k at the interval [−1, 1], and we have limited the variation of the order Δu_k at the interval [-10, 10]. The triangular and trapezoidal membership functions, the max-

min reasoning method, and the defuzzification method are all included in this paper because they have been widely cited in the literature [7, 24].
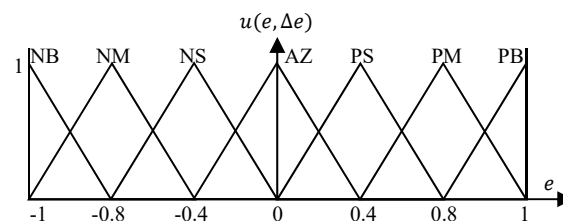

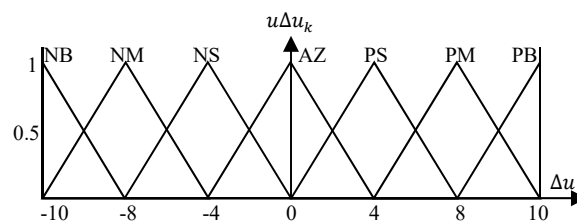Fig.5. Error membership function and error variation.

Fig.6. Membership functions of the order variation.

5.2 Rule base

A fuzzy system is characterized by a set of linguistic expressions (rules) based on expert knowledge. This knowledge is usually represented as "If _Then" rules [22, 28]. The collection of these rules forms the socalled rule base or rule set of the fuzzy controller. A fuzzy rule is called a Fuzzy Associative Memory (FAM) because it associates between input fuzzy sets and output fuzzy sets. For example:

− Rule i: If e_k = PM and Δe_k = NS Then Δu_k = PS.

We have chosen our rules in such a way that the deviation between the set point and the actual output can be recorded in an inference table, as shown in Table1. This table contains the two input variables e_k and Δe_k an output variable that represents the variation of the control set point Δu_k. Each of the variables evolves on a reference set or several fuzzy subsets are defined. Fuzzy subsets are noted as follows: PB: Positive Big, NB: Negative Big, PM: Positive Medium, PVS: positive very small, NS: Negative small, PS: Positive Small, NS: Negative Small, AZ: About Zero.

The extraction of fuzzy rules is a rather delicate point to solve. The usual methods consist in extracting the first set of rules by questioning an expert. This first set of rules can then be adjusted as the command is executed. The inference rules for our system are represented by an inference matrix according to table 1. The values in these cells were determined logically by studying all possible combinations of the input variable convince ourselves of this, we will study a few cases:

Table 1. The rule base rules 49 rule.

Δe_k ╲ e_k	NB	NM	NS	AZ	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	AZ
NM	NB	NG	NG	NM	NS	AZ	PS
NS	NG	NG	NM	NS	AZ	PS	PM
AZ	NG	NM	NS	AZ	PS	PM	PB
PS	NM	NS	AZ	PS	PM	PB	PB
PM	NS	AZ	PS	PM	PB	PB	PB
PB	AZ	PS	PM	PB	PB	PB	PB

If e_k is NB and Δe_k is NB: This is the situation where the error is negative big and the variation of the error is negative big. From an automatic point of view, this means that on the one hand we are below the desired set point and on the other, we are getting further and further away from

the desired set point. Logically, we will try to make a large negative correction, so the change in Δu_k will be (NB). We can see that the contents of the cells considered in this table effectively correspond to the controller.
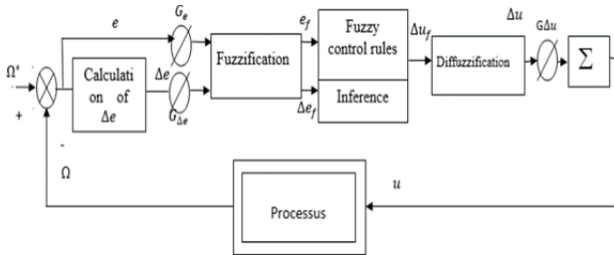

Fig.7. Control block diagram with fuzzy controller.

5.3 Development of the fuzzy controller

Figure 7 illustrates the diagram proposed for a single input/single output system. The reason for the successful use of fuzzy algorithms in complex industrial systems is the choice of methods that are relatively practical and allow the development of such algorithms with notable simplicity. These approachellow to the expression of a set of decisions in linguistic terms, which use fuzzy sets to describe the magnitudes of the error, its variation, and the appropriate control. By combining these rules, decision tables can be compiled to give the values of the controller output corresponding to the situations of interest [12].

The scaling factors should be chosen based on the system study so that the permissible range for the error and its variation are not exceeded during small transient events. In the case of fuzzy logic control, triangular forms are generally used for membership functions. Although there are no precise rules for the definition of membership functions, some general guidelines are given, to lead to a suitable choice.

5.4 Control law

This control law is a function of the error and its variation $(u = f(e, \Delta e))$. Therefore, activating the associated set of decision rules gives the variation in the command Δu needed, thus allowing the adjustment of such a command u. The most general form of this control law is:

(12) $u_{k+1} = u_k + G_{\Delta u}\Delta u_{k+1}$

The fuzzy controller receives as input the speed error and its variation. The quantities manipulated by the controller are fuzzy sets, which require a conversion of the numerical values in input it is the defuzzification. According to these fuzzy variables and the decision rules, the fuzzy controller calculates the fuzzy value of the command, it is the inference. It is then sufficient to transform this fuzzy value into a digital value, which is defuzzification. The control scheme is given in Figure 8.

5.5 Adaptive gain blur controller

In the literature on fuzzy control, the gain related to the variation of the control is taken as constant. However, this increases the response time of the system. To solve this problem, a decision table on the gain is required to increase the dynamic performance of the system in table1. From the control decision table, its variation between times t_k and t_{k+1} is given by:

(13) $u_{k+1} = u_k + G_{\Delta u_{k+1}}\Delta u_{k+1}$

The interest in variable gain in this approach is to ensure adequate system stability and adapt the fuzzy algorithm to each situation of the system. We must therefore consider the gain as a fuzzy variable whose different fuzzy sets must

be defined. Each fuzzy set of the control corresponds to a fuzzy set of the gain, of the same nature but is always strictly positive. We choose an adaptive gain fuzzy set, and its corresponding membership function is represented as follows.
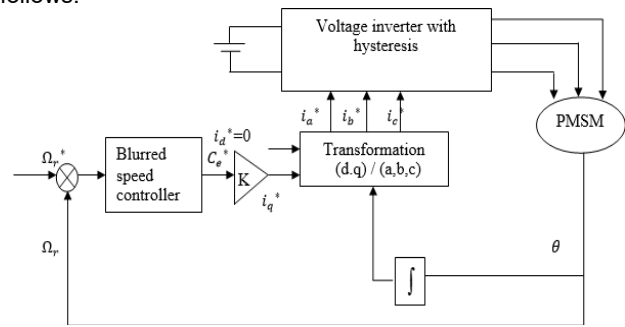

Fig.8. Schematic diagram of MSAP with fuzzy controller.

Table 2. Decision table for the gain control.

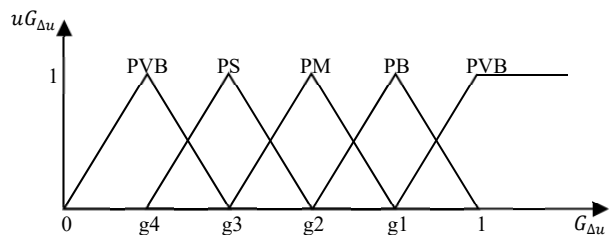| Δe \ e	NB	NM	NS	AZ	PS	PM	PB
NB	PVB	PVB	PB	PM	PS	PVS	PVS
NM	PVB	PB	PM	PS	PBS	PVS	PVS
NS	PB	PM	PS	PVS	PVS	PVS	PS
AZ	PM	PS	PVS	PVS	PVS	PS	PM
PS	PS	PVS	PVS	PVS	PS	PM	PB
PM	PVS	PVS	PVS	PP	PM	PB	PVB
PB	PVS	PVS	PS	PM	PB	VB	PVB

Fig.9. Gain membership function of the control.

The following diagram, Fig.10 shows the description of the fuzzy controller with adaptive control gain. We use the designed controllers for monitoring the induction command and to demonstrate the accuracy of the developed process, with the machine factors in table 3.
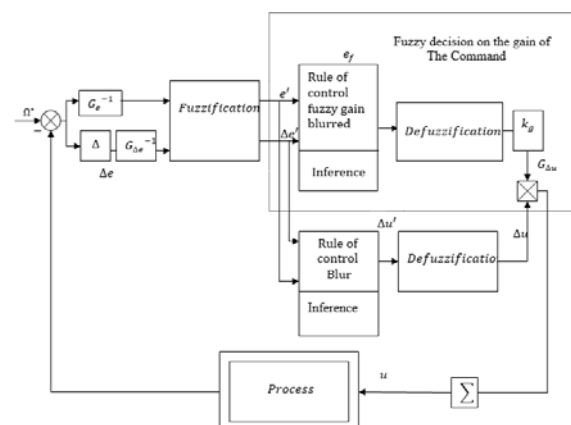

Fig.10. Schematic of a fuzzy controller with adaptive gain.

Table.3. The parameters of the machine (PMSM).

Parameters	Value	Parameters	Value
$R_s(\Omega)$	1.4	J(Nms /rad)	1.76 e-3
L_d(H)	0.0066	f_c(Ns/rad)	38.818 e-5
L_q(H)	0.0058 H	C_r(N.m)	5
φ_f(Wb)	0.1546	P	3

6. Simulation results and discussion

Different simulations have been executed with Matlab, Simulink, speed, torque and flow monitoring of the permanent magnet synhcron machine, the simulation results are provided and discussed.

With the application of a load torque (C_r = 5N.m) at time t = 0.15s, then a removal of the load at t = 0.25s, followed by a velocity inversion from 314rad/s to −314rad/s) at time t = 0.3s. The obtained results are illustrated in figure 11.

We can see that the velocity is a reference value of 314 rad/s and the flux is fixed at this value (0.155 Wb). In the absence of load, it stabilizes at a value that compensates for wear effects (0.5 Nm), the implementation of a resistive torque increases the developed electromagnetic torque. The reversal of the speed set point shows that this inversion is associated with a slight increase in the stator current and the electromagnetic torque.

To validate the approach used, we have investigated the effect of the uncertainty in the model to be controlled and the influence of parameter variations on the performance of the speed control. We consider variations in the stator resistance and the inductances. For this purpose, we increase the resistance to $10 \times R_s$ and decrease the inductances by 20%. The results of the simulation in Fig. 12 show the PI control sensibility to the variation of the stator resistance and the variation of the cyclic inductance. We can observe that the decoupling is kept, which is due to the robustness of the controller.
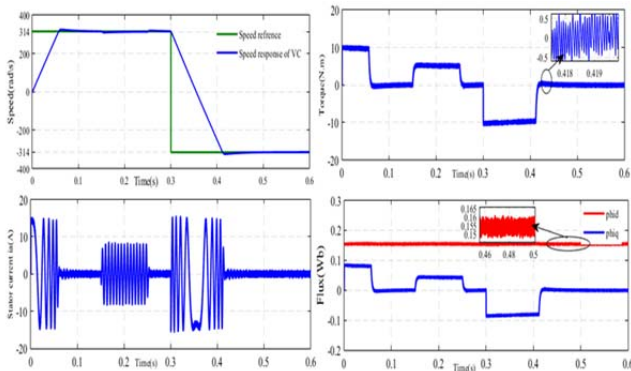

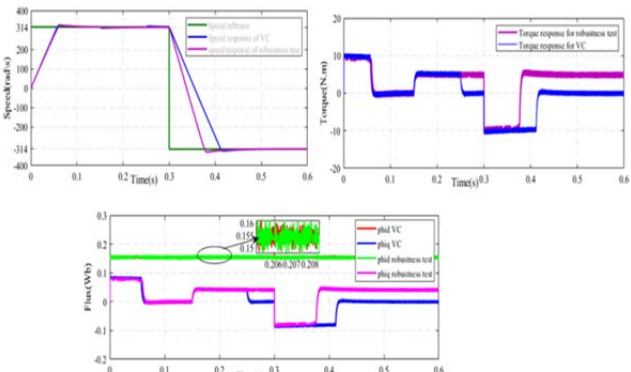Fig.11. Simulated results of Speed monitoring by victor control.

Fig.12. Variation stator resistance by $10 \times R_s$ and the inductances L_d, $L_q - 20\%$.

The system designs of the controllers can be seen in Figures (8 and 10), which are related to the fuzzy controller and the adjustment of the control gain. The system reactions of the first test concerning a starting at no load, followed by the application of a load torque between 0.15 and 0.25s.The second test concerns a reversal of the reference speed from (314rad/s to -314rad/s) at t = 0.3s. Figures (13 and 14) the speed follows its reference value, with a very small overshoot after a very small response

time, the flux is installed, so provides a large torque at start-up. These results show that the application of a resistive torque hardly affects the desired speed, with very fast disturbance rejection observed, which leads to an increase of the developed electromagnetic torque as well as the stator current of the machine with sinusoidal behavior. When changing the reference, the direction of rotation is reversed without overshooting in a very short response time.
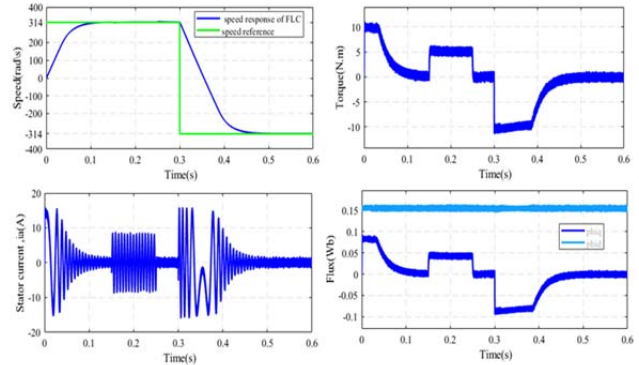

Fig.13 .Speed control of the PMSM with the fuzzy controller, when applying an application of torque in the period [0.15 0.25s].
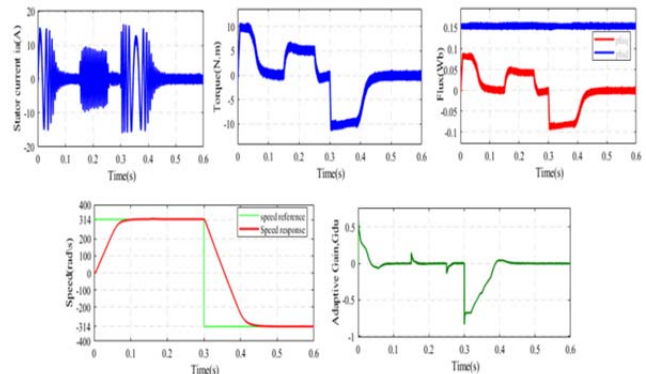

Fig.14. Speed control of the PMSM with an adaptive fuzzy controller, when a load torque is applied during the time interval [0.15 0.25s].

The curve speed behavior of the system with adaptive gain fuzzy controller (AGFLC) is faster than that without adaptation (FLC) and shows a decrease of overshoot compared with the control by a regulator with a constant gain, also the effective value of the adaptive gain, we notice the control gain intervention with important values during the changes of the set point and relatively small values along the steady state, which provides good stability of the system.
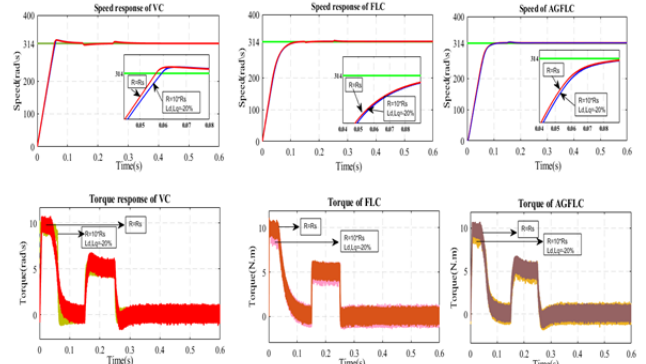

Fig.15. Reliability test against by $10 \times R_s$ and 20% decrease of L_d, L_q of VC control, FL control, and AGFL control.

When modifying the characteristics of the machine (stator resistance and cyclic inductance), figure 15 shows that the dynamics of the set point pursuit and the system decoupling are not influenced by the variations changes introduced on the parameters of the machine, as well as the adaptive gain fuzzy control has a superior ability to minimize overshoot compared to fixed gain fuzzy and vector control.

7. Conclusion

In this work, the speed and flow control of the PMSM is simulated in MATLAB/Simulink with the use of the AGFLC for the direct rotor field-oriented control approach of the PMSM drive system. Two methods are used to study the speed regulator of PMSM.

The first approach considers the traditional control structure with (PI) controller. Secondly, the modern speed control of the permanent magnet synchronous motor powered by variable frequency for the PMSM drive system. The monitor strategies are based on vector control, fuzzy logic, and adaptive gain fuzzy controller.

The simulation results confirm the effectiveness of the AGFL, exhibiting satisfactory dynamic performance, high robustness and overall stability, fast response without overshoot, short settling time at low speed with minimal response, and optimal immunity to parameter changes. and external disturbances (stator change resistance about 10* Rs and inductance L_d, L_q increase by 20%, sudden change in converter speed, sudden change in load torque). In the end, the AGFLC monitor is regarded as a major step in the progress of intelligent control, not just for PMSM but also for all other machinery. In future work, the experimental realization of the proposed intelligence of the proposed control system will be considered.

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