PERFORMANCE COMPARISON OF CONTROL TECHNIQUES APPLIED OF A PERMANENT MAGNET SYNCHRONOUS MACHINE

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Abstract. *The Permanent Magnet Synchronous Machine (PMSM) presents wide application in general industry as motor, in wind power system as generator and in electrical vehicles in motoring or generating modes. This machine has several advantages over others AC or DC machines as high power density, high efficiency and low cost of maintenance. In this context, this paper presents a study and a model simulation of control techniques applied to this electric machine. The main purpose is to compare the control techniques, through of simulations, and evaluate the best output response. Initially are studied the characteristics and employability of the PMSM and a classical dynamic model in d-q reference frame is analyzed. The vector control system of the PMSM is applied using the d-q reference frame theory. The space vector modulation is also analyzed due its common use on three-phase motor drive and its simplicity and easily implementation in an embedded system. In addition, it is accomplished the development of the inner loop current control and the external loop speed control for the PMSM, in this case are used two control techniques, the PI control and an adaptive PI using Fuzzy logic. A PI control is used due its simplicity and good output response. An adaptive PI is tuned by fuzzy logic due to its ability to adapt the control action according to operating conditions such as disturbance or load variations. Simulations results in Matlab/Simulink to validate model control system design are presented.*

Keywords: *Control, PI, Fuzzy, PMSM*

1 INTRODUCTION

The AC motors are commonly used in industrial applications due to their simplicity, ruggedness and low cost. The permanent magnet synchronous motor (PMSM) is an ac synchronous motor with fixed rotor flux generated by permanent magnets mounted on the surface or interior of the rotor. When the high power density and high efficiency are fundamental issues, as the electric and hybrid vehicles applications, the permanent magnet synchronous motors (PMSMs) are considered the most appropriate electrical machine. As the rotor flux of the PMSM is generated by the permanent magnetic there is no field current or rotor current in this machine. Therefore, there are no rotor currents losses in the PMSM and this improve its efficiency and consequently reduce the power consumption.

The PMSM requires a power converters electronics to achieve de adjustable speed operation with high performance. Despite its advantages, the PMSM is a nonlinear system and its control remains complicated especially when a good dynamic performance applications is required.

Traditionally, the cascaded PI controllers for speed and current are used in the PMSM drive in spite of its nonlinear model. The PI controllers with fixed gains cannot provide capability of the high performace in all range operation.

Artificial intelligent techniques such as ArtificialNeural Networks (ANNs), Genetic Algorithms (GAs) and Fuzzy Logic (FL) can be used to deal with the great difficult of the tradicional PI control in the nonlinear systems. These nonlinear techniques can be used to self-tune the controller and adapt it against changes in the process (Salami and Cain, 1995). Therefore, a PI controller incorporated by one of these intelligent techniques can be more robust to load variations, parameter changes, abnormal modes of operation, etc.

An offline tuning strategy of a PI controller and a FLC for brushless DC motor and PMSM was successfully carried out in Demirtas (2011); Öztürk and Çelik (2012), respectively. In [8], the PI controller parameters were adjusted simultaneously by a fuzzy inference and it was concluded that the proposed approach increased the robustness of the controlled system by adapting the controller parameters to changes in the process. In addition to these mentioned intelligent studies, more similar papers are presented by Ahn et al. (2007); Bagis (2007, 2011); Kumar et al. (2006).

Fuzzy control does not depend on the mathematic model of the system, and its algorithm is easy to design. The fuzzy PI regulator not only has the advantages of the PI controller, such as simple, stability, and reliability, but also has the merits of the fuzzy controller, such as quick response and small overshoot (Deng et al., 2015).

In this paper, are proposed a FLC based PI controller and a conventional PI for the PMSM speed control drive. For this, is used the vector control strategy with constant torque angle in the motor drive. The dynamic response obtained is improved through of using of fuzzy PI when compared to the PI controller. Section 2 describes the modeling of the PMSM used in this work, also describes the vector control, motor drive and the controllers. Section 3 presents the controller design using PI controller and fuzzy based PI controller. The results and discussions are presented in section 4 and finally the section 5 relates the conclusions and the contributions met in this work.

2 General theoretical consideration

2.1 Modeling

The PMSM presents greater robustness, better torque/inertia ratio, better dynamic response, high flux density in the air gap compared with DC and induction motors. And yet, the use of permanent magnets in place of the field windings causes the PMSM has fewer losses, better efficiency, less volume and weight and simpler modeling.

In this paper, the control technique applied to PMSM is performed through vector control with constant torque angle. The vector control theory is applied in AC machines to enable the decoupling between the torque and the flow.

The vector control is based on the regulation of the current i_d and i_q on the motor, so the torque angle is defined as the angle between the axis current D and Q axis. Thus, this control strategy maintains the torque angle by 90º and the i_d current is kept at zero, causing the proportional torque to the magnitude of current quadrature axis (Krishnan, 2001).

This type of control can be characterized by the following relationship:

$$\begin{aligned} i_q &= i_s \\ i_d &= 0 \end{aligned} \tag{1}$$

Thus, the mathematical model of the MSIP in reference D and Q axis of the rotor is given by Eq.(2) and Eq.(3) (Singh et al., 2016).

$$\begin{aligned} V_d &= R_s i_d + L_d i_d - L_q \omega_r i_q \\ V_q &= R_s i_q + L_q i_q + L_d \omega_r i_d + \psi_f \omega_r \end{aligned} \tag{2}$$

$$\begin{aligned} \psi_d &= L_d i_{d+\psi_f} \\ \psi_q &= L_q i_q \end{aligned} \tag{3}$$

The motor dynamics is given by Eq.(4)

$$T_e - T_m = J\frac{d\omega}{dt} + B\omega \tag{4}$$

The Eq.(5) represents the torque electromagnetic produced by PMSM.

$$T_e = \frac{3}{2}P[\phi_m + (L_d - L_q)i_d]i_q \tag{5}$$

Where:

- V_d - D axis voltage;
- V_q - Q axis voltage;
- R - Stator phase resistance;

- L_d - D axis indutance;
- L_q - Q axis indutance;
- i_d - D axis current;
- i_q - Q axis current;
- ψ_d - D axis flux linkage;
- ψ_q - Q axis flux linkage;
- ψ_f - Permanent magnet flux linkage;
- ϕ_m - Permanent magnet flux;
- ω - Rotor eletrical angular speed.

2.2 Controllers

In the control of the PMSM, it is very common to use industrial controllers of the proportional-integral type (PI). Seeking an improvement in the dynamic performance of the system according with the charge variations or in the reference signal, an adaptive PI controller tuned by Fuzzy logic is approached.

Usually a well-designed PI tends to get a good output response through the desired parameters. However, through variations of the system, these outputs may suffer some kind of variation. In this way, the adaptive PI control tuned by Fuzzy logic can perform the immediate correction of the control parameters, through system variations.

In the most cases, the design of PI type controllers uses as technique, the place of roots, which consists of adjusting the poles and/or zeros of the controller to cancel the undesirable poles and/or zeros of the original system (Sá et al., 2010). In this paper, the PI control strategy of the PMSM is implemented in the cascade form with the inner current loop and a external speed loop.

In recent years, the PI type controller for PMSM, has been widely used in various industrial fields. However, the fixed coefficients of the PI controller must be basead a precise mathematical model to guarantee the performance of the control (Tursini et al., 2002).

However, it is inevitable that the uncertainties caused by parametric and dynamic variations of the PMSM are present. This makes the fixed coefficients of a conventional PI controller do not guarantee the robustness of the system. Since most PMSM drive systems in industrial applications are controlled with PI controllers,there is a growing demand to optimized define the PI parameters in real time according to the varying operating conditions so get a better system response.

For the fuzzy control, the error and error variation are normally used as controller inputs. The inputs of the fuzzy control establishes a degree of pertinence based on the fuzzy sets, this procedure is called fuzzification. The defuzzification procedure calculates the effective control through the rules, for a given set of variables (Luiz et al., 1997).

The adaptive PI, through fuzzy logic, performs adjustments on controller gains K_p and K_i instantly to ensure robustness of the system. Figure 1 illustrates the structure of the adaptive PI through fuzzy logic.

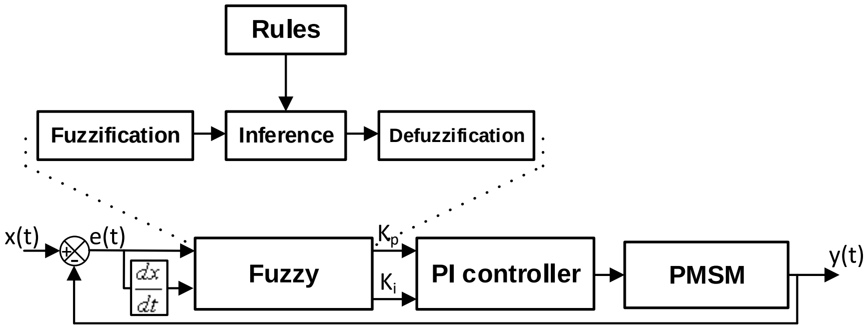

Figure 1: Structure of an adaptive PI governed by Fuzzy.

3 Controller design

For the control of the PMSM, the rotor speed (ω_r) and the currents of the direct axis and quadrature (i_d and i_q) must be controlled. In this way, the control is formed by an external loop, which performs the speed control, and two inner loops, which control the currents i_d and i_q.

The input signal of the speed controller corresponds to the comparison of the measured speed signal (ω_r) and the speed reference signal (ω_r*). The output of the speed controller is the reference signal of the quadrature axis current controller (i_q).

The currents measured at the output of the PMSM are transformed to the reference axes D and Q, the difference of the currents measured with the reference currents (i_d* and i_q*) are the input signal for the currents controllers. The output of the currents controllers are the components of the voltage vector in reference axes D and Q.

The voltage signals from the output of the currents controllers are converted to the reference α and β to perform the PWM modulation of the inverter that powers the PMSM. This transformation is necessary to obtain a two-phase rotating system.

Finally, the PMSM is powered by the converter. A schematic of this process can be seen in Fig. 2.

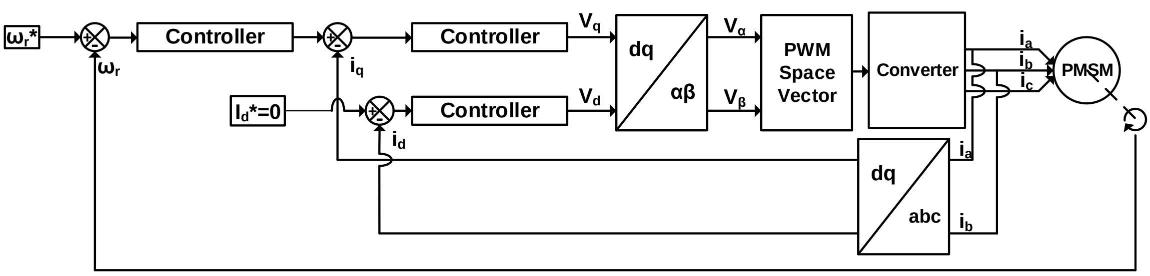

Figure 2: Schematic of the vector control of PMSM.

3.1 PI controller design

For a quick performance of speed and torque in PMSM, was initially used three controllers PI type. One for external loop of speed and the other two on inner loop of dq currents.

The design of the PI controllers is based on a linear control developed from the transfer functions derived from the mathematical modeling of the PMSM. Using models in the discrete domain (z plane), the results of the projects are the K_p and K_i gains. Equation(6) and Eq.(7) represent the first order transfer functions of the electric dynamics and of the mechanical dynamics, respectively.

$$Ge(s) = \frac{1}{sL_d + R_s} \tag{6}$$

$$Gm(s) = \frac{1}{Js + B} \tag{7}$$

The transfer functions are discretized using the Z-transform with a zero order hold and a sampling time of 50μs. Using the mathematical model of the transfer function in the Z domain, a PI controller can be designed, so that the closed loop system presents a response with a low settling time and a null-error in steady state.

For this, the design criteria of the PI controllers of this work are the settling time and the overshoot of the system. The overshoot value used for the three PI controllers is 10%. The settling time of the currents controllers is three times smaller than the motor's electrical time constant, while the speed controller settling time is ten times smaller than the mechanical time constant of the PMSM.

Through the design criteria of the controllers, it was possible to determine by means of calculations the values of the proportional and integral gains of the PI controllers. The gains of the controllers PI of speed and the i_d and i_q currents are shown in Table 1. The difference in the gain of the currents controllers is due to the difference in the inductance values of the D and Q reference axes, since the transfer function for both is the same.

Table 1: Gains PI controllers.

PI controllers	K_p	K_i
Inner loop current i_d	18,0911	0,6213
Inner loop current i_q	35,6162	1,1976
External loop speed	0,4501	$3{,}0103 \cdot 10^{-4}$

3.2 Fuzzy controller design

The PMSM control using adaptive PI controllers governed by fuzzy logic seeks an improvement in the dynamic performance of the system, since the PMSM does not present linear dynamics. The adaptive PI controller governed by fuzzy logic is composed of an adjustable PI controller and a fuzzy controller (Fig. 1). Initially, this work uses this type of control for the external loop only, composed of two inputs and two outputs that adjust the gains of the PI controller.

In order for the fuzzy controller to make adjustments to the gains of the PI controller, it is necessary that the conventional PI controller receive some modifications. Thus, the outputs of the fuzzy controller can be incremented in the PI controller gains in real time. Figure 3 illustrates the adaptive PI used.

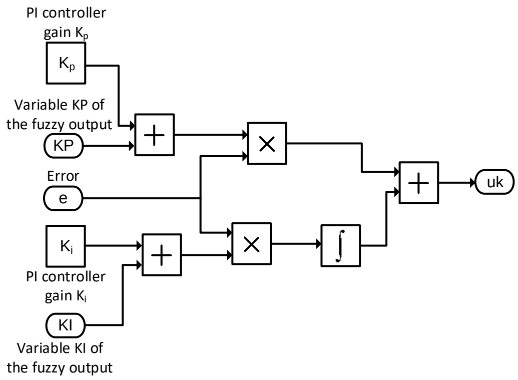

Figure 3: Adaptive PI Controller.

The fuzzy logic is basically divided into two parts: fuzzification and defuzzification. Fuzzification happens in the initial stage, it is the stage where the linguistic variables are defined subjectively. The defuzzification in turn is the step at which the resulting regions are converted to the output variable. The fuzzy controller design can be divided into four steps (Wang et al., 2007):

- Definition of input variables and output variables;
- The system variables are transformed into fuzzy variables;
- Criação das regras fuzzy através do conhecimento do sistema pelo projetista;
- Settling output parameters.

The input variables of the fuzzy controller are error (E) and derivative of the error (EC), with range from [-6,6] through five triangular membership functions, as illustrated in Fig. 4. They are: NG, NP, ZO, PP and PG, representing the error and/or derived of the error as negative big, negative small, zero, positive small and positive big, respectively. The two outputs of the fuzzy

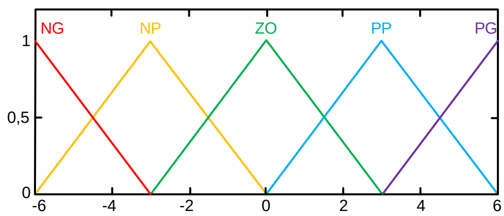

Figure 4: Membership functions of the E and EC.

controller are the KP and KI gains that are incremented in real time in the PI controller. The of output variables range from [0, 9], with triangular pertinence functions represented by Z, P, M and G (zero, small, medium and big). Figure 5 illustrates the output variables KP and KI. The

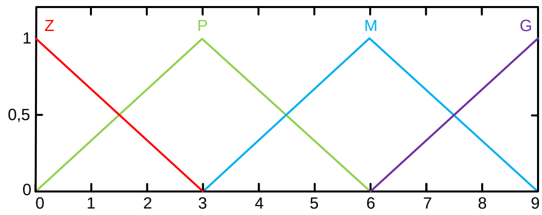

Figure 5: Pertinence functions of the KP and KI.

factors of each variable is who dictates the importance of each variable of the fuzzy system, and must be chosen properly so that the controller has a good performance. Once the fuzzy logic is empirical, the values of each of the factors were adopted considering the results of experiments and simulations of the PMSM.

The values of the factors found for the speed loop are: for the variables E and EC are K_E = 1 and $K_E C$= 1, for the output variables KP and KI we have $K_K P$ = 1,2 and $K_K I$ = 21, 1, respectively.

The fuzzy rules are created through the knowledge of the system by the designer. The controller output response can influence the dynamics and performance of the system. These outputs can influence the stability, response time, overshoot, and system accuracy.

For the PMSM, the logic implemented is according to the following items (Wang et al., 2007):

- When E is very big, we must take a big KP to have a good performance. We should also take a KI = 0 to avoid a big overshoot;
- When E and EC have an acceptable value, we must take a small KP so that the system has a small overshoot. Since KI will not have much influence on the system, an appropriate KI is must take;
- When E is too small, a big values of KP and KI should be take to make the system stable.

Table 2 and Table 3 represent the rules for the variables KP and KI, respectively

The outputs of the fuzzy controller are regulated from the 25 state conditions obtained from the fuzzy rules. The output variable is obtained by MIN-MAX inference. The exact value of KP and KI are obtained after defuzzification, in this work the defuzzification method used is the centroid.

The main difficulty using an adaptive PI controller governed by fuzzy logic is to establish the correct values of the output variables of the fuzzy controller, since they have a great influence on the system response. In this case, the knowledge of the system by the designer is essential, since empirical knowledge is one of the main characteristics of fuzzy logic.

Table 2: Set of fuzzy rules for KP.

EC	E				
	NG	NP	ZO	PP	PG
NG	G	G	G	G	M
NP	M	G	P	P	P
ZO	M	G	Z	P	G
PP	P	P	P	P	P
PG	M	G	G	M	G

Table 3: Set of fuzzy rules for KI.

EC	E				
	NG	NP	ZO	PP	PG
NG	Z	Z	Z	Z	Z
NP	M	M	M	M	M
ZO	G	G	Z	G	G
PP	P	M	M	M	M
PG	Z	P	G	G	G

4 Results and discussion

In this section the results obtained in the simulations performed in the PMSM with the discrete PI control and the adaptive PI governed by fuzzy logic are presented. The system simulation was performed using the block diagram in Matlab Simulink tool.

The PMSM was subjected to the starting transient, variation in the speed reference and load variation. The simulations show the variations of speed (ω_r), currents i_d and i_q, and electromagnetic torque (T_e).

The gains of the PI controllers used were presented in Table 1 of the previous section. For the fuzzy PI controller gains, it initially uses the same PI controllers gains, however, they are incremented or decremented in real time according to the fuzzy rules established in Table 2 and Table 3.

For the simulations, a calculation step of 1μs is used, while the step of calculating the controllers is 50μs. The switching frequency of the PWM is 10kHz. The simulation time ranges from 0 to 4 seconds, with variation in the speed reference in 1.2s and 2.4s, and step of charge in the times 0,6s, 1,8s and 3s. The parameters of the PMSM used are presented in Table 4.

Table 4: PMSM parameters.

	Parameters	Values
P	Number of pole pair	2
R_s	Stator resistance	0,8Ω
λ	Magnet flow	0,399595 Wb
L_q	Quadrature axis inductance	0,0405 H
L_d	Direct axis inductance	0,021 H
J	Inertia	$0{,}0247 Nm/rad/s^2$
B	Static friction	0,0057 Nms

4.1 Results PI Controllers

The simulation results of the PMSM are presented considering the PI controllers, for the inner loop of currents i_d and i_q, as well as for the external loop of speed. A simulation drawing can be seen in the Fig. 6.

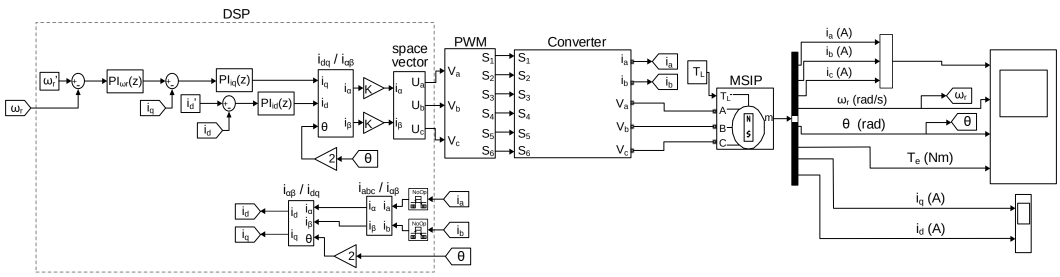

Figure 6: PMSM simulation model with discrete pi control for inner loop and external loop.

The behavior of the speed, the setting time of the PMSM and the speed signal, through the variations in the system can be seen in Fig. 7. In starting of PMSM, speed error causes the PI controller to seek the null-error, which the speed reaches its reference value. In 0,6s, a step of charge causes again the speed error to not be null, again causing the controller to seek error equal to zero.

Other steps of charge happen in time 1,8s and 3s. However, at the times 1,2s and 2,4s different speed reference values are applied. In Fig. 8 it is possible to observe the speed error present in the system during the simulation time.

Figure 9 shows the behavior of the i_d and i_q currents. It is observed that the current i_d is taken to zero due to the strategy used to control the constant torque angle, prevaling only the current i_q. The currents values follow well the reference values, showing the good performance of the currents controllers. Through the constant torque angle control strategy (i_d = 0), the torque is determined by the current i_q. This equivalence of the current i_q with the conjugate was already expected, proving the good functioning of the controllers' designs. Figure 10 shows the

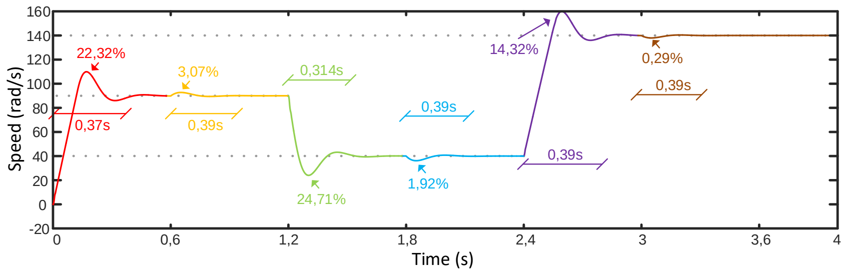

Figure 7: Behavior of the PMSM speed using PI type controllers for inner loops and external loop.

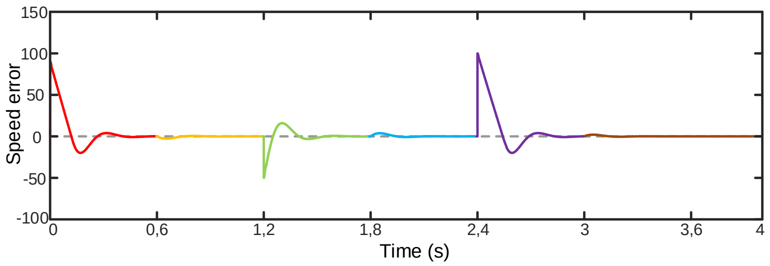

Figure 8: Behavior of the PMSM speed error using PI type controllers for inner loops and external loop.

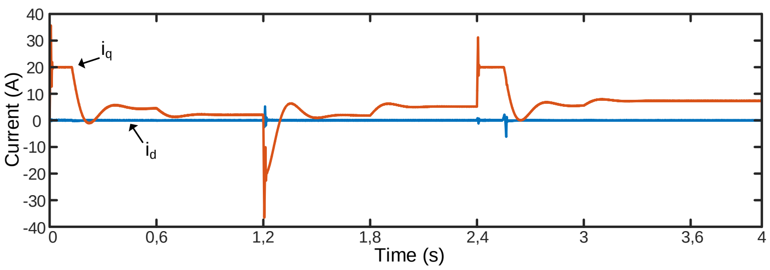

Figure 9: Behavior of the i_d and i_q currents of the PMSM using PI type controllers for inner loops and external loop.

electromagnetic torque of the PMSM, which compared to the current response i_q, proves the equivalence of the current with the conjugate.

The results of the simulation of the PMSM, for the discrete PI type controllers, obtained a good result. The simulation was performed through conditions that approximate the maximum possible of the real. It is possible to observe from the figures that the speed follows the reference value of the system, presenting a good response to the applied charge and speed steps, maintaining null error in steady state.

4.2 Results of adaptive PI governed by fuzzy logic

Through the adaptive PI controller governed by fuzzy logic designed, the PMSM simulation is performed using this control only for the external loop of speed as seen in the Fig. 11

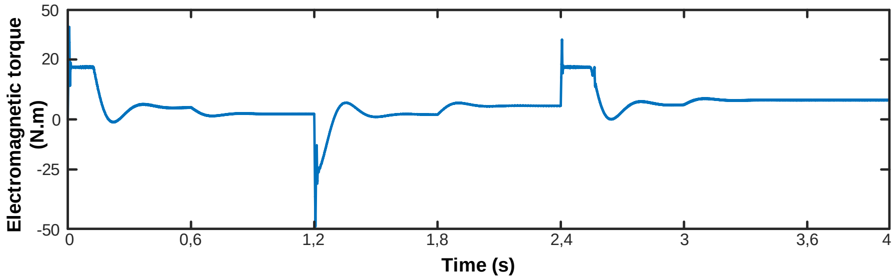

Figure 10: Behavior of the electromagnetic torque of the PMSM using PI type controllers for inner loops and external loop.

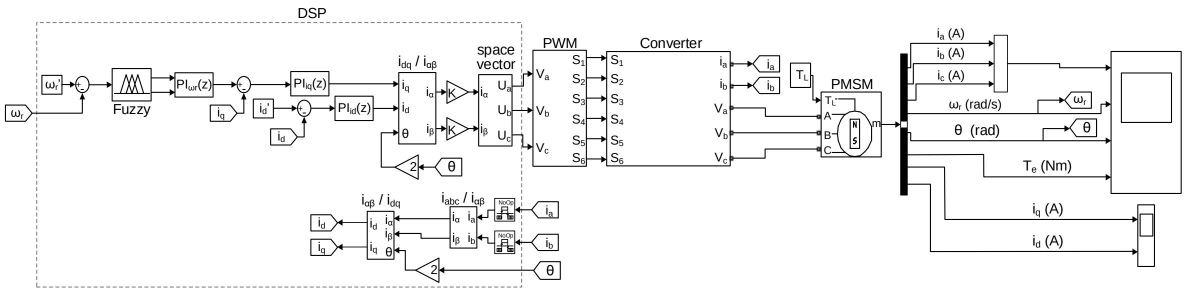

Figure 11: PMSM simulation model with adaptive PI control governed by fuzzy logic for external loop of speed.

In Fig. 12 it is possible to observe the speed behavior of the PMSM over time, with the charge steps and speed reference, through the fuzzy adaptive PI control.

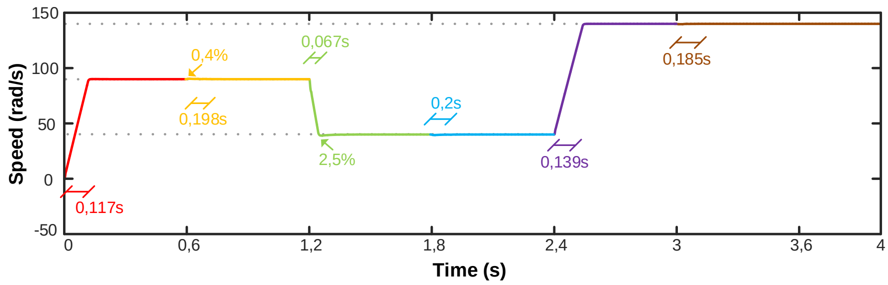

Figure 12: Behavior of the PMSM speed using adaptive PI governed by fuzzy logic for external loop of speed.

In this case, the speed behavior becomes better when compared to the PI controller, presenting a low overshoot and even in some cases null. In addition, the settling time became smaller in all applied steps, presenting null-error in steady state as seen in Fig. 13

In Fig. 14 it is possible to visualize the i_d and i_q currents of the PMSM simulation using the adaptive PI controller through the fuzzy logic in the external loop of speed. The i_d is taken to zero because of the applied control strategy, however, it is possible to observe that the current

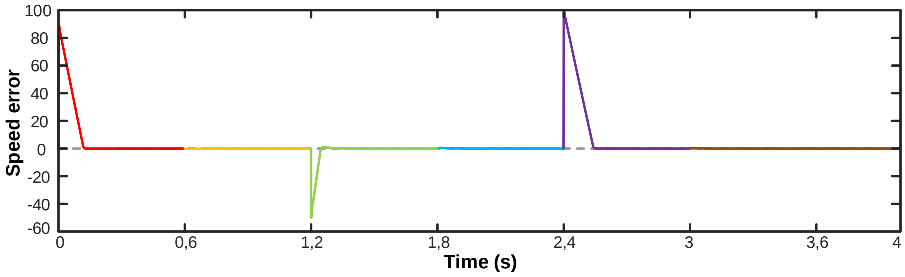

Figure 13: Behavior of the PMSM speed error using adaptive PI governed by fuzzy logic for external loop of speed.

i_q has smaller variations, when compared to the model simulated only with PI controllers, since the speed controller is responsible for providing its value of reference.

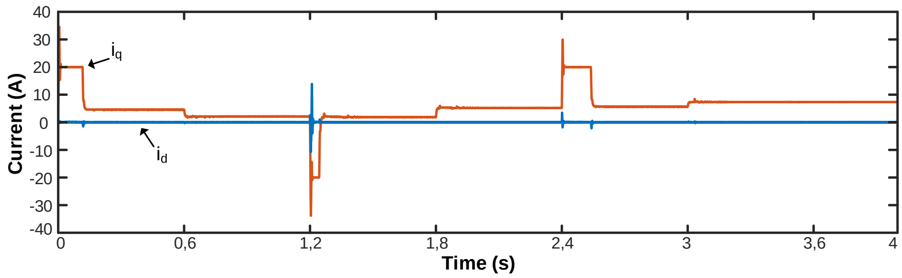

Figure 14: Behavior of the i_d and i_q currents of the PMSM using adaptive PI governed by fuzzy logic for external loop of speed.

This lower variation in the current i_q, causes the three-phase current that feeds the PMSM to have a smaller variation. Figure 15 compares three-phase currents of the PMSM simulation using PI controller for the external loop, with simulation using adaptive PI governed by fuzzy logic in the external loop.

Comparing the three-phase currents of both simulated models, it is easy to see that using an adaptive PI controller by fuzzy logic in the external loop of speed, the variations of the currents become smaller, occurring only when a charge step or speed reference is applied.

As the conjugate is determined by the current i_q through the constant torque angle control strategy (i_d = 0), the electromagnetic torque in this case also presents a smaller variation, as observed in Fig. 16

In this section, we were performed the simulations and comparisons of the types of controllers applied to the PMSM, through vector control with constant torque angle. The Table 5 and Fig. 17 shows a comparison of the simulation results of speed of the MSIP for the types of controllers designed.

The Table 5 shows all values of overshoot and settling time, for the charge steps and speed reference. All values presented were obtained through Matlab using the 'stepinfo' command.

Is evident through the Table 5 and Fig. 17, that the adaptive PI tuned by fuzzy logic com-

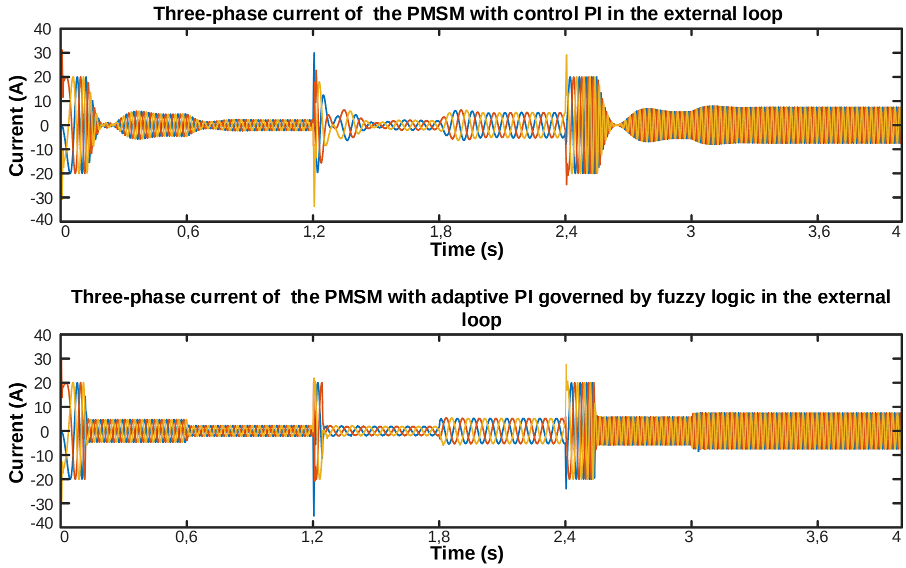

Figure 15: Comparison of the behavior of PMSM three-phase currents.

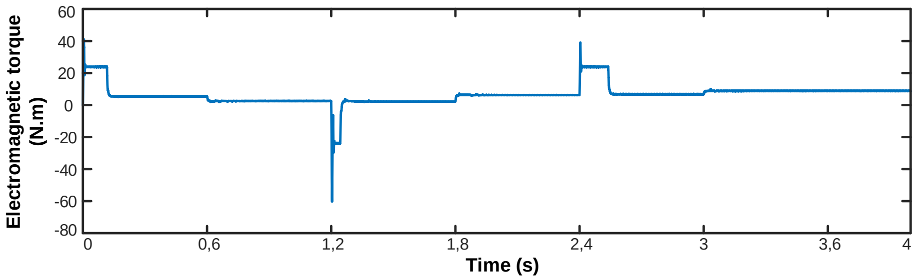

Figure 16: Behavior of the electromagnetic torque of the PMSM using adaptive PI governed by fuzzy logic for external loop of speed.

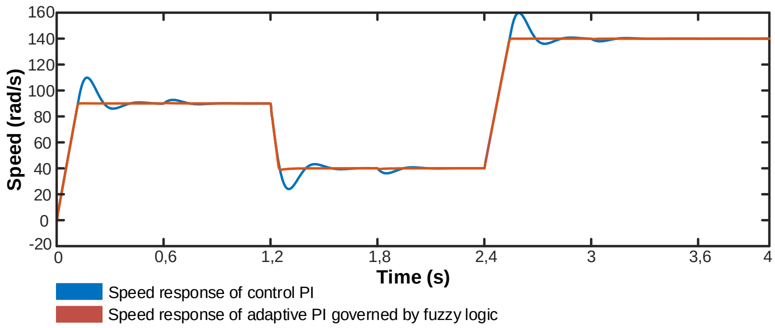

Figure 17: Comparison of the simulation results for the speed of the PMSM.

paring with traditional PI control has the better dynamic and static response performance of the PMSM, obtaining shorter settling time and overshoot.

Table 5: Performance comparison of PMSM simulations.

	Speed control	
Time	PI control	Adaptive PI governed by fuzzy logic
0s - 0,6s (start)	22,32% - 0,37s	0% - 0,117s
0,6s - 1,2s (charge step)	3,07% - 0,39s	0,4% - 0,198s
1,2s - 1,8s (speed reference)	24,71% - 0,314s	2,5% - 0,067s
1,8s - 2,4s (charge step)	1,92% - 0,39s	0% - 0,2s
2,4s - 3,0s (speed reference)	14,32% - 0,39s	0% - 0,139s
3,0s - 4,0s (charge step)	0,29% - 0,39s	0% - 0,185s

5 Conclusion

This work had the objective of studying the performance of controllers for the PMSM, applying the vector control strategy with constant torque angle in the motor drive.

The PI controller, applied to the PMSM, does not present a good result through the dynamic variations applied during the simulation, obtaining a high overshoot and settling time, when compared to the other controller studied. Since PMSM is a nonlinear motor, the use of traditional linear controllers makes it difficult to perform these controllers. In contrast, the adaptive PI by fuzzy logic presents good results of overshoot and settling time to the same steps used in the simulation. Besides these advantages, the fuzzy controller does not need a mathematical model of the system, however, it needs knowledge of the system by the designer.

The simulation results show that the adaptive PI governed by fuzzy logic presents lower overshoot and settling time when compared to traditional PI control. The fuzzy controller uses the error and the derivative of the error of the speed to adjust the PI controller parameters online during the simulated period. Introducing a greater robustness of the control system.

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