# SWITCHED RELUCTANCE MOTOR SPEED CONTROL BASED ON AN ADAPTIVE FUZZY SYSTEM: EXPERIMENTAL TESTS, ANALYSIS AND CONCLUSIONS

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***Abstract* – In this paper, the controller tuning and performance of a speed controller prototype for a Switched Reluctance Motor is presented. The system using a new robust control structure is proposed by combining auto-tuning fuzzy logic control (*FLC*) and *PID* auto-tuning based on relay technique. Simulation and Experimental essays are analyzed and discussed to show some advantages of having a learning Switched Reluctance Machine (*SRM*) speed controller.**

***Keywords* - Switched Reluctance Machine, Fuzzy Logic Controller, PID Controller.**

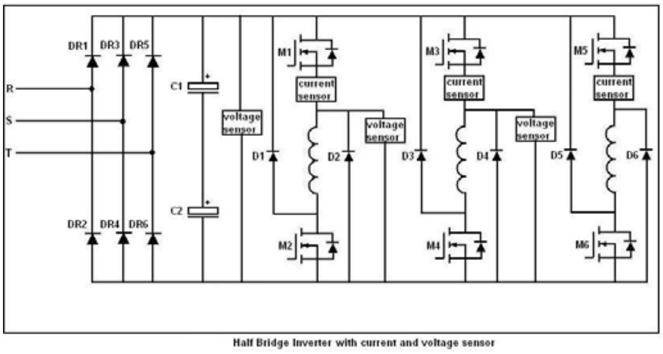
## I. INTRODUCTION

Designs for controller of Switched Reluctance Machines (*SRM*) have been target of an intense interest by researchers for the past decade. The task of the controllers is to achieve optimum control performance overcoming torque ripple problems in sensorless applications, as well as problems in the speed control. Solutions for these problems have been presented with relative success and innovation [1, 2, 3, 4, 5, 6]. Despites the huge development in control theory, the majority of the *SRM* application is controlled by the well-established proportional plus integral plus derivative (*PID*) controller. In order to implement a *PID* control, three parameters must be set for a given process. Normally, the parameters need on-line retuning if the process presents a poor performance due to plant parameter variations or non-linearities. Sometimes, it is difficult to find an appropriate set of control parameters that ensures stabilization when there are setpoint and/or load change [7]. A possible solution to deal with complex processes is the implementation of control systems based on knowledge and learning like a Fuzzy Logic controller (*FLC*). *FLC* methods have gained popularity in the last years both in industry and research communities and many methodologies of *FLC* design have been proposed in the literature and applied to nonlinear control problems [8]. Recently researches of Electrical Engineering Department at Federal University of Ceará has been developing an experimental speed controller prototype for *SRM* that uses an digital *PID* controller based on Åström and Hägglund's relay technique [9, 10] and to overcome the *PID* drawback a *FLC* type *PID* is being implemented. The *FLC* is a combination of the auto-tuning fuzzy *PID* method suggested in [11, 12] and the *FLC* gain scheduling method discussed in [13 and 14]. The results made in test show that, using this speed controller the operating characteristics of SRM can be improved greatly, and the control precision also can be enhanced obviously. This paper is organized as follows. In Section II, the description of the structure of *SRM* power control drive is presented. Aspects of controllers design and the way of combining the *PID* and *FLC* approaches are considered in Section III and IV. In section V, simulation and experimental tests for tracking setpoints of *PID* conventional control and auto-tuning fuzzy approaches are discussed. Conclusions and future works are presented in Section VI.

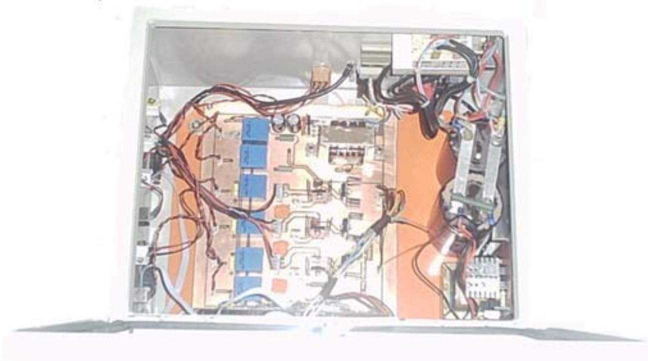
## II. STRUCTURE OF SWITCHED RELUCTANCE MOTOR DRIVE (SRM)

The *SRM* used in this work is a 12/8 machine, which means 12 stator poles, with 2 excitation phases, and 8 rotor poles [6, 15]. Dealing with the SRM, a method for identification of parameters of the machine has been first effectuated to obtain the characterization of the machine [15]. In the system of *SRM* drive, the core controller collects and processes signals and gives out all kinds of control demand, so the control strategies are achieved in system. The structure of the power system of switched reluctance motor drive is shown in figure 1.

The power converter structure has six power *MOSFETS* and six freewheeling diodes needed to de-energize each phase and protect the switches during the inverse voltage operation, figure 1. The power converter is supplied by continuous voltage from a rectifier bridge. This converter topology has been explained in detail in [15]. It makes possible an individualized phase operation by using three voltage levels (-V, 0 and V), but has the disadvantage of using 2N switches for N motor phases.




(a)



(b)

Fig. 1. (a) half bridge inverter with current and voltage sensor (b) inverter circuit

## III. CONVENTIONAL PID CONTROLLER

The aim of conventional *PID* controller design is to provide some insight in the problems of fuzzy scale determination. Ziegler and Nichols have developed simple tuning rules to find the *PID* controller parameters based on the step response of the open-loop (reaction method) or closed-loop (oscillation method) systems (conventional methodology). In order to implement a *PID* control, three parameters ($K_p$, $T_i$ and $T_d$) must be set for a given process.. The discrete *PID* control Law is given by

$$u(k) = K_p e(k) + K_i ie(k) + K_d de(k) \tag{1}$$

where *e(k)* is the error, *de(k)=(e(k)-e(k-1))/T* is the change of error and *ie(k)=ie(k-1)+Te(k-1)* is the numerically approximated integral of error.

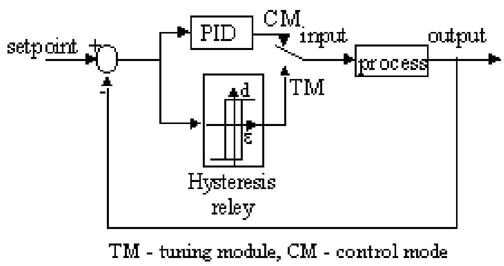



Figure 2. Auto-tuning *PID* controller.

Considering the auto-tuning context, the *PID* tuning parameters ($K_p$, $K_i$ and $K_d$) can be determined by automatic rules that account for phase and amplitude margins specifications [8] and using the relay feedback experiment, figure 2. The control scheme is simple from **a** computational viewpoint, is easy to be understood by process operators, and can be supervised by the user.

## IV. FUZZY PID GAIN SCHEDULING CONTROL (*FPID-GS*)

The *FLC* type *PID* implemented is a combination of the auto-tuning *PID* method and the *FLC* gain scheduling method suggested in [12, 13]. The *PID* auto-tuning approaches is based on relay technique. This technique is able to identify the process ultimate gain, $K_u$, and ultimate period, $T_u$, through a few relay cycles. Theses values are used to adjust fuzzy scale factors. So, in the *FPID-GS* scheme the controller parameters are changed on-line as a function of operation conditions. Figure 3 depicts the used configuration.

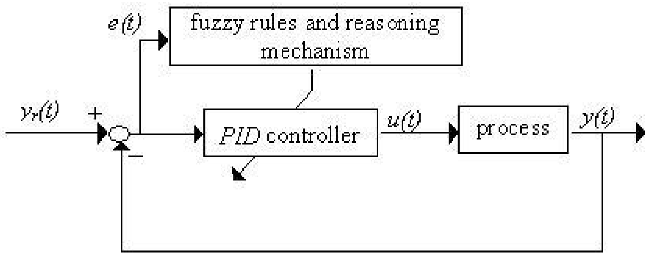



Fig. 3. Fuzzy gain scheduling *PID* scheme.

In this scheme the *PID* parameters are in prescribed ranges [$K_{p,min}$; $K_{p,max}$] and [$K_{d,min}$; $K_{d,max}$]. These parameters are normalized by the following: The integral time $T_i$ and the integral gain $K_i$ are determined with reference to the derivative time constant as shown in [13, 14]. The rules have the following general structure:

If *e(t)* is $A_i$ and $\Delta e(t)$ is $B_i$ then $K_{p,i}$ is $C_i$ and $K_{d,i}$ is $D_i$ and $\alpha = \alpha_i$ ; $i$=1,2 ...,$m$

(2)

where $A_i$, $B_i$, $C_i$ and $D_i$ are fuzzy sets on corresponding supporting sets, $\alpha_i$ is a constant and *m* is the number of rules. The fuzzy sets $C_i$ and $D_i$ may be either *Big* or *Small* and they are characterized by the sigmoid membership function and the rules base are shown in table 1.

**Table I**

**Fuzzy tuning rules for $K'_p$, $K'_d$ and $\alpha$.**

| $K'_p$ | | Δe(t) | | |
|---|---|---|---|---|
| | | NS | ZO | OS |
| **e(t)** | NS | B | B | B |
| | ZO | S | B | S |
| | PS | B | B | B |

| $K'_d$ | | Δe(t) | | |
|---|---|---|---|---|
| | | NS | ZO | PS |
| **e(t)** | NS | B | S | B |
| | ZO | B | B | B |
| | PS | B | S | B |

| $\alpha$ | | Δe(t) | | |
|---|---|---|---|---|
| | | NS | ZO | PS |
| **e(t)** | NS | 3 | 2 | 3 |
| | ZO | 3 | 3 | 3 |
| | PS | 3 | 2 | 3 |

By using the proposed membership function the following condition can be set up [13]

And the defuzzification is obtained by:

$$K'_p = \sum_{i=1}^{m} \mu_i K'_{p,i} \qquad K'_d = \sum_{i=1}^{m} \mu_i K'_{d,i} \qquad \alpha = \sum_{i=1}^{m} \mu_i \alpha_i \tag{3}$$

where $K'_{p,i}$ and $K'_{d,i}$ are the values of $K'_p$ and $K'_d$, respectively, corresponding to the grade $\mu_i$ for the $i$-th rule. The implemented *FLC* algorithm consists of following steps: *i*) identify the process ultimate gain and the ultimate period through the relay test; *ii*) determine fuzzy scales factors*; iii)* determine $K_{p,min}$, $K_{p,max}$, $K_{d,min}$ and $K_{d,max}$; *iv*) normalize the controller parameters $K_p$, $K_d$ by Ziegler-Nichols frequency method; *v*) determine the parameters $K'_p$, $K'_d$ and $\alpha$ by a set of fuzzy rules of the form (2); *vi)* calculate the parameters $K_p$, $K_i$ and $K_d$; *vii*) apply the calculate parameters to the closed loop *PID* controller; *viii*) if any set-point changing, repeat from the step (ii), the other form repeat from the step (iv).

## V. SIMULATION AND EXPERIMENTAL RESULTS

In this part, some simulation and experimental results are given to illustrate the design capability of the *FPID-GS* control method.

### *A. Simulation Results*

For simulation purpose the characteristics of the *SRM*, the same used in experimental test, are summarized as follow: rated current = 2,5A; rated speed=6000rpm ; number of phase=3; number of stator pole=12; number of rotor pole=8; aligned phase inductance=52mH; unaligned phase inductance=8mH; phase resistance=3,5Ω; DC voltage supply=120V. Figure 4 shows the simulation of the *FPID-GS* controller for a ramp set-point tracking. According to the simulation results it is possible to observe an adequate behavior for the process outputs (minimum overshoot and fast stabilization). In simulation test a white noise (variance 0,01; rated noise to signal 0.02 approximately) was added to SRM speed output as a sensor noise.

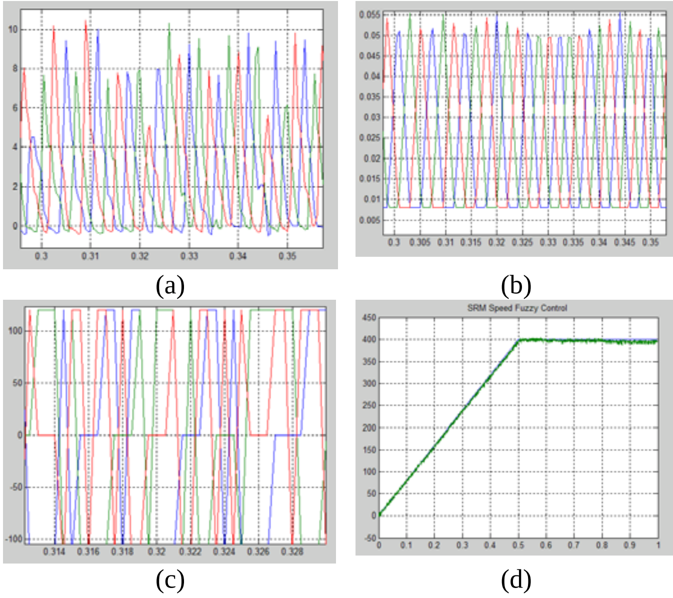



Fig. 4: *FPID – GS* simulation results (a) phases currents ($i_a$, $i_b$ and $i_c$ in rd/s); (b) Phases inductances ($l_a$, $l_b$ and $l_c$); (c) Phases voltages switching ($v_a$,$v_b$ and $v_c$)

Figure 5 shows the evolution of the *PID* controller. Although the *FPID-GS* presented better tracking performance than *PID* control algorithms, the *PID* provided an appropriate dynamic behavior.

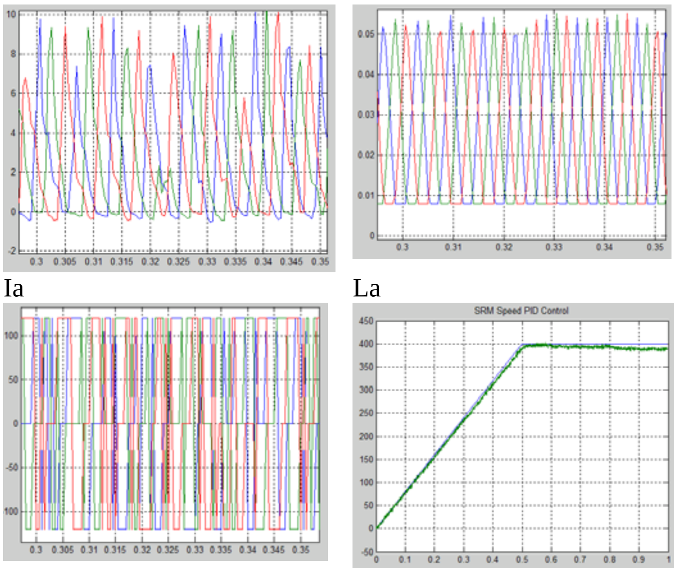



Fig. 5: *PID* simulation results (a) phases currents ($i_a$, $i_b$ and $i_c$ in rd/s); (b) Phases inductances ($l_a$, $l_b$ and $l_c$); (c) Phases voltages switching ($v_a$,$v_b$ and $v_c$)

Beside the graphical presentation, the Controller's performance can be quantified by *MPE* (mean percentage error) and *MAPE* (mean absolute percentage error) indexes, expressed in 4

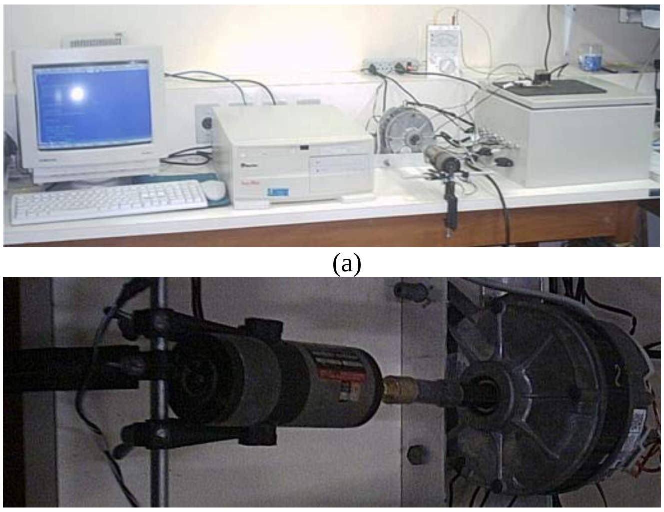
$$MPE = \sum_{i=1}^{n} \frac{PE_i}{n} \qquad MAPE = \sum_{i=1}^{n} \frac{|PE_i|}{n} \qquad PE_i = \frac{(\omega - \omega_{ref})}{\omega_{ref}} 100 \tag{4}$$

Being PE the percentage error of the speed, given by $PE$ and $i \in N+$.

To evaluate simulation numerical performance of the *FPID-GS* control in comparison with *PID* control the *MPE* and *MAPE* indexes are calculated. The indexes show that the *FPID_GS* (*MPE*=-0,0001, *MAPE*=10.053) compares favorable with *PID* controller (*MPE*=-0,008; *MAPE*=11,98).

### *B. Experimental Results*

The *SRM* experiment setup is presented in figure 6. The system is composed by a *SR* motor, a power driver, as presented in section II, and a data acquisition board *PC* (Personal Computer) based. Speed, current and voltage are controlled by three 16 bits 10MHz PWM channels, six 12 bits A/D inputs and a 10 bits gray code encoder. This prototype was designed in Department of Electrical Engineering at Federal University of Ceara and has been used to evaluate *SRM* control algorithms. Further information about this plant is available in *http://www.gpar.dee.ufc.br*.



(a)

(b)

Fig. 6: (a) experiment set up (b) SRM and load

The laboratorial tests were set up by a trapezoidal speed reference function between 0 and 1000 rpm as presented in figure 7.

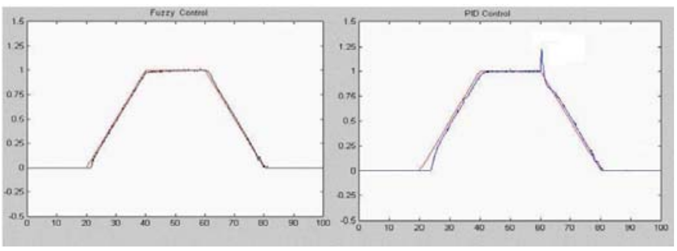



Fig. 7: Speed tracking with a trapezoidal reference function [1000ω (rpm) x Time (s)]. (a) *FPID-GS* control, (b) *PID* control.

The experiment results in figure 7 show that the *FPID-GS* controls effectively the speed tracking. Better results are obtained with *FPID-GS* than *PID* controller. Results denote that the characteristics of SRM can be greatly improved with designed controller.

Performance indexes indicate that experimental *FPID-GS* control compares favorable with *PID* control. The *MPE* and *MAPE* indexes are *FPID_GS* (*MPE*=0,032, *MAPE*=1.35) and *PID* controller (*MPE*=0,521, *MAPE*=4.05).

## VI. CONCLUSION

A scheme for design auto-tuning gain scheduling *PID* fuzzy controller was described to Switched Reluctance Machines (*SRM*) speed control. Experimental results of the system are presented along a set of tracking speed reference functions. To evaluate purpose two kind of error measures was used to controllers, namely the *MPE* (mean percentage error) and *MAPE* (mean absolute percentage error). The auto-tuning gain scheduling fuzzy *PID* controller derived successfully demonstrated better performance than the conventional *PID* controller for *SRM* speed control for its nonlinear feature and adaptation capacity.

Future research is directed to experimental evaluation of auto-tuning gain scheduling *PID* fuzzy controller when applied to the current loop of Switched Reluctance Machines. Different load set up should be implemented for tracking and robustness performance evaluate. By using nonlinear systems will be possible to examine the issue of robustness in the context of model parameter error and plant/model mismatch.

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