An Intelligent Self-Tuning PI Type Fuzzy Logic Controller for a Switched Reluctance Motor Drive

S. Vijayan, S. Paramasivam, R. Arumugam, M. Vasudevan, and S. Palaniswami

Abstract—This paper presents an application of self tuning fuzzy control technique for a Switched Reluctance Motor (SRM) Drive. In this research, the output-scaling factor (α) is adjusted in online by the gain tuning Fuzzy Logic Controller (GTFLC) rules according to the current status of SRM. The rule base of GTFLC for tuning the output SF is defined on error (e) and change of error (Δe) of the controlled variable using triangular equally overlapped membership functions (MF’s). The proposed self-tuning technique is applied to PI-type FLC to conduct real time implementation of speed control for SRM. The proposed scheme shows a remarkably improved performance over its conventional PI type FLC. A prototype based on a 6/4 pole SRM drive has been constructed and used to practically verify the features of the proposed control strategy. The complete speed control algorithm of the SRM drive incorporating the STPIFLC is experimentally implemented and validated using a high-speed digital signal processor board TMS320F2812. It is shown that the presented STPIFLC for SRM drive is with fast tracking capability, less steady state error, robust to load disturbance and very less torque ripple.

Index Terms—Speed control, STPIFLC, switched reluctance motor (SRM), PI-FLC, PD-FLC, digital signal processor, TMS320F2812.

I. INTRODUCTION

SWITCHED Reluctance motor (SRM) has an intrinsic simplicity and low cost that makes them well suited to many applications. Furthermore, the motors have a high robustness due to the ability to operate with the loss of one or more motor phases and are thus well suited to operate in harsh industrial environments [1], [2]. A SRM is a rotating electric motor, where both stator and rotor have salient poles. The stator winding comprises a set of coils, each of which is wound on one pole. The rotor is made from laminations in order to minimize the eddy current losses. The rotor tries to get to a position of minimum reluctance by aligning itself with the stator magnetic field when the stator winding are excited [1], [2]. Due to its attractive features of high power density, high efficiency and low maintenance cost, SRM is widely used in high performance servo applications, such as aerospace, industrial and robotics [1]-[10]. SRM cannot be run directly from the supply. It can be run only when the motor is integrated with power converter, controller and rotor position sensor. Many papers have been reported on the performance simulation of SRM with experimental validation for different control strategies such as a feed back linearization control, variable structure control, fuzzy logic control, self tuning control and four quadrant operation of SRM [11]-[17]. None of these papers have achieved very low RMSE during various operating conditions. Hence, it is necessary to design a STPIFLC for SRM to get the optimum performance in the presence of the parameters variations and load disturbances. This paper proposes a STPIFLC where in both discrete PI type FLC and GTFLC algorithms are combined to get the desired performance of SRM. This controller employs only with the speed error and changes in speed error and produces an equivalent control term. The designed STPIFLC enhances system performance in transient and steady state. This paper is organized as follows. Section II reviews the SRM description. Section III discusses the PI type and PD type FLC implementation. Section IV explains the STPIFLC implementation. Section V presents the experimental setup. Section VI discusses the results. The conclusion is given in the last section.

II. SRM DESCRIPTION

The SRM has a salient pole stator with concentrated windings and also a salient pole rotor with no magnets or coils. The basic principle of torque production is discussed in [1], [2]. In this study, a prototype 3 phase, 6/4 pole SRM is considered and is shown in Fig. 1. The prototype motor parameters are given in the Appendix. All the three phases are assumed to be identical. Hence, all the equations are described with respect to the generic phase (j=1, 2 and 3). Due to symmetrical location of the poles, mutual inductances between the phases are neglected. The phase flux linkage \(\psi_{j}(\theta_{i}, i_{j})\) is a nonlinear function of the rotor position and the phase current. The flux linkage vs. current characteristics for various rotor positions is given in Fig. 2. The discrete mathematical model of the SRM is a set of controlled difference equations obtained by the use of standard SRM theory. The difference equations that describe the dynamics of SRM are approximated as follows
where \( v_{jn} \) is voltage across the \( j \)th phase at \( n \)th instant, \( i_{jn} \) is current of the \( j \)th phase at \( n \)th instant, \( i_{jn-1} \) is current of the \( j \)th phase at \( (n-1) \)th instant, \( R_j \) is resistance of the \( j \)th phase, \( L_{jn} \) is inductance of the \( j \)th phase at \( n \)th instant, \( L_{jn-1} \) is inductance of the \( j \)th phase at \( (n-1) \)th instant.

\( \psi_{jn} \) is flux linkage of the \( j \)th phase at \( n \)th instant, \( \psi_{(n-1)} \) is flux linkage of the \( j \)th phase at \( (n-1) \)th instant, \( \Delta \) is sample time, \( J \) is moment of inertia, \( B \) is viscous friction coefficient of the motor-load system, \( \theta_n \) is rotor position at \( n \)th instant, \( \theta_{n-1} \) is rotor position at \( (n-1) \)th instant.

From (1), it is understood that the motional voltage of each phase is proportional to the angular velocity and rate of change of inductance with respect to rotor position [1], [2]. According to the (4), the electromagnetic torque \( T_m(\theta_n,i_{jn}) \) produced by the SRM phase is directly proportional to rate of change in co energy. It is understood that the motor creates positive torque in the direction of increasing flux linkage and negative torque in the direction of decreasing flux linkage. Hence it is required to choose proper rotor position to get the proper control of the SRM.

In order to achieve the better control and speed response in all regions, it is required to design STPIFLC controller.

### III. PI and PD Type Fuzzy Logic Controller Implementation

Fuzzy logic controllers (FLC’s) have been reported to be successfully used for a number of nonlinear processes and complex systems [18]. A comprehensive review on the design and implementation of FLC’s can be found in [19]–[21]. It is known that FLC consists of fuzzification process, knowledge base and defuzzification process [21]. In the case of a PI-type FLC, the actual value of the controller output is obtained by the following equation (8)

\[
u(k) = u(k-1) + \Delta u(k)
\] (8)

Where \( u(k) \) is Controller output, \( u(k-1) \) is \((k-1)\)th instants controller output, and \( \Delta u(k) \) is incremental change in controller output.

In the above (8), an accumulation of controller output takes place outside the FLC and is not directly reflected in the rules themselves. The block diagram for STPIFLC can be
used for PI-type FLC and PD type FLC, if the GTFLC’s output is disabled. In case of PI type FLC, speed error ($e\_{n}$) and change of speed error ($\Delta e\_{n}$) are the input variables and ($\Delta u\_{n}$) is the output variable and PD type FLC, input variables are same as that of the PI type FLC and $u\_{n}$ is the output variable (not $\Delta u\_{n}$). Fig. 4 (a) shows membership functions of input variables ($e\_{n}$ and $\Delta e\_{n}$) and output variable ($\Delta u\_{n}$ and $u\_{n}$), wherein conventional triangular shapes and with 50% overlapping is selected.

As shown in Fig. 3 (a), each membership function is assigned with seven fuzzy sets, which are negative Large (NL), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive large (PL). The rule bases for PI-type and PD type FLC is formed by experience gained during practical experiments on SRM in open loop operation. Table I and II show the linguistic rule bases for PI-FLC and PD-FLC respectively. The most important difference between these two linguistic rules is the selection of switching boundary at which the sign of rule change. In the case of PI-FLC, the switching boundary is diagonal and for PD-FLC is horizontal line along speed "$e\_{n}$" equals zero.

The operation of PI type FLC can be explained with the following example. From the Fig. 3 (a) and (b), it is understood that the error ($e\_{n}$) is 0.6 and the change in error ($\Delta e\_{n}$) is -0.625. For the considered example, there are four rules are invoked as shown in Table I. By Table I (bolded linguistic variable), these four rules and inference results are:

**Rule 1:** if $e\_{n}$=PM and $\Delta e\_{n}$=NL then $\Delta u\_{n}$=NS;

**Rule 2:** if $e\_{n}$=PM and $\Delta e\_{n}$=NM then $\Delta u\_{n}$=Z;

**Rule 3:** if $e\_{n}$=PL and $\Delta e\_{n}$=NL then $\Delta u\_{n}$=Z;

**Rule 4:** if $e\_{n}$=PL and $\Delta e\_{n}$=NM then $\Delta u\_{n}$=PS;

The membership grade values corresponding to $\Delta u\_{n}$ are obtained from a singleton membership function, $\Delta u\_{n}$, as shown in Fig. 3 (a). Once the fuzzy inference results are obtained from the inference engine, the actual control output is obtained from the defuzzification process to get the crisp output. In this research, the inferred fuzzy control action is converted to a crisp value, $\Delta u$, through the commonly used center of area (COA) method to obtain

$$\Delta u = \sum_{N=1}^{4} \frac{\Delta u_{N} \mu_{N}}{\sum_{N=1}^{4} \mu_{N}}$$

where $\Delta u$ is Grade value of $\Delta u_{N}$, which is obtained from the fuzzy inference results and membership function, $\Delta u$ as shown in Fig. 3 (a) $\mu_{N}$ is weighting factor, obtained by using Mamdani’s minimum fuzzy implication rule.

When the error is 0.6, the $\mu_{PM}[e\_{n}=0.6]$ and $\mu_{PS}[e\_{n}=0.6]$ are calculated by the simple triangular geometry and its equation (10) is given as

$$\mu_{\pm}(x) = \begin{cases} 0 & x \leq a \\ \frac{x-a}{b-a} & a \leq x \leq b \\ \frac{c-x}{c-b} & b \leq x \leq c \\ 0 & c \leq x \end{cases}$$

The degree of membership for the considered error ($e\_{n}$) is $\mu PM[e\_{n}=0.6]=0.6$ and $\mu PS[e\_{n}=0.6]=0.4$ and its diagrammatic representation is shown in Fig. 4 (a). Similarly for change in error ($\Delta e\_{n}$)=-0.625, $\mu PM[\Delta e\_{n}]$ is "NL" and "NM". The membership grade value for $\mu_{NL}[\Delta e\_{n}=-0.625]$ and $\mu_{NM}[\Delta e\_{n}=-0.625]$ are calculated by the simple triangular geometry as explained above. The degree of membership for the change in error ($\Delta e\_{n}$) is $\mu_{PS}[\Delta e\_{n}=0.5]$ and $\mu_{PL}[\Delta e\_{n}=0.5]$ and its diagrammatic representation is shown in Fig. 4 (b). The details to obtain the weighting factor $\mu_{N}$, $N=1, 2, 3$ and $4$ are obtained by Mamdani’s minimum implication rule and as given below.
\[
\mu_1 = \min\{\mu_{N_e(e_N = 0.6)}, \mu_{N_e(e_N = -0.625)}\} = \min\{0.6, 0.5\} = 0.5
\]
\[
\mu_2 = \min\{\mu_{N_e(e_N = 0.6)}, \mu_{N_e(e_N = -0.625)}\} = \min\{0.6, 0.5\} = 0.5
\]
\[
\mu_3 = \min\{\mu_{N_e(e_N = 0.6)}, \mu_{N_e(e_N = -0.625)}\} = \min\{0.4, 0.5\} = 0.4
\]
\[
\mu_4 = \min\{\mu_{N_e(e_N = 0.6)}, \mu_{N_e(e_N = -0.625)}\} = \min\{0.4, 0.5\} = 0.4
\]
\[
\Delta u \text{ For PI –FLC is found as follows}
\]
\[
\Delta u = \frac{\Delta u_{\mu_1} + \Delta u_{\mu_2} + \Delta u_{\mu_3} + \Delta u_{\mu_4}}{\mu_1 + \mu_2 + \mu_3 + \mu_4} = -0.01388
\]
\[
\text{Similarly for PD –FLC is found as follows}
\]
\[
u = \frac{u_{\mu_1} + u_{\mu_2} + u_{\mu_3} + u_{\mu_4}}{\mu_1 + \mu_2 + \mu_3 + \mu_4} = 0.25
\]

IV. SELF TUNING FLC IMPLEMENTATION

In the previous section, the complete implementation of PI type and PD FLC for SRM drive is explained. It is well known that PI type FLC is robust to load disturbance or sudden change in reference speed, it has got significant steady state error during steady state [22], [23]. The performance of PI-type FLC’s for higher order systems, systems with integrating elements or large dead time, and also for nonlinear systems may be very poor due to large overshoot and excessive oscillation. Such systems may be ultimately uncontrollable [24]. In [25], Palm proposed to achieve the optimal adjustment in the input SF with the help of input–output cross-correlation function, though he assigned a higher priority to the tuning of output SF over that of input SF’s. Li and Gatland [26] also have given more emphasis on the tuning of input and output SF’s than that of ME’s or rule base. Maeda and Murakami [27] proposed fuzzy rule-based schemes for adjustment of input–output SF’s as well as for tuning of control rules for Takagi–Sugeno (TS) model. In [28], Rajani K. Mudi and Nikhil R. Pal, proposed scheme, wherein output scaling factor (SF) is adjusted on-line by fuzzy rules according to the current trend of the controlled process. Among all the proposed methods, the [28], can easily be applied to SRM control. None of the researchers have tried to implement the same for SRM drives. In this research, we tried the STPIFLC for practical implementation of SRM drives. Fig. 3 shows the block diagram of the presented STFLC.

As shown in Fig. 5, the STFLC consists of a combined effect of PI-FLC and GTFLC, thereby a high performance control action can be achieved under transient and steady state. From [28] it is understood that the overall gain of the STPIFLC is \(\alpha G_u\), not simply \(G_u\). In the case conventional PI-FLC, the value of \(G_u\) is maintained constant throughout the entire operating conditions, then the controller is said to be PI type FLC. But, the gain of the proposed STPIFLC does not remain fixed while the controller is in operation, rather it is changed in each time step by the gain scaling factor \(\alpha\), depending on the actual speed of the SRM. The rule base for gain scaling factor \(\alpha\) is given in Table. III. Thus, the proposed controller is simply an adaptive feedback loop controller. The functional relationship between output and input of a GTFLC is given as

\[
\alpha(k) = f(e(k), \Delta e(k))
\]
also implemented.

controllers, a controller of PI, PI-FLC and PD-FLC is

advantages of a proposed STPIFLC with other

transistor (MRD5009) are used to sense the rotor position

sensors are mounted on the shaft of the SRM, wherein a

SRM is equipped with a rotor position sensor. The three

Texas Instruments as a development tool board [30]. The

computer (PC), driving circuit, classic bridge converter

subsystems, which consists a 6/4 pole SRM, personal

to indicate which of the three phases of the SRM is to be

excited as the motor runs. One of the rotor position

sensor’s output is used to calculate the actual speed of the

SRM. The controller is implemented by software and

Table III show the linguistic rule bases for GTFLC. For

example, if error is PL and change of error is NL then the

SRM drive system moves towards the reference speed at

high speed due to controller action. To avoid large

overshoot, the controller gain αGTFLC should be kept very

low. After experimentation, it is found that control action

of the STPIFLC is more nonlinear and very smooth than

that of its PI-FLC. In the proposed STPIFLC, the controller

output is generated by the continuous and nonlinear

variation of α. The most important point to be noted is

that GTFLC is independent of parameter variation. The

overall gain (α) of GTFLC for the considered error and

change in error is found as follows

\[ α = \frac{α_{1}μ_{1} + α_{2}μ_{2} + α_{3}μ_{3} + α_{4}μ_{4}}{μ_{1} + μ_{2} + μ_{3} + μ_{4}} = 0.28472 \]  

(18)

The overall gain (α) of GTFLC is varied form 0-1 for

different operating conditions. To emphasize the

advantages of a proposed STPIFLC with other

controllers, a controller of PI, PI-FLC and PD-FLC is also

implemented.

V. HARDWARE SYSTEM DESCRIPTION

The drive system is made up of several distinct

subsystems, which consists a 6/4 pole SRM, personal

computer (PC), driving circuit, classic bridge converter
[29], sensing circuitry and the ezDsp F2812 board from

Texas Instruments as a development tool board [30]. The

SRM is equipped with a rotor position sensor. The three

sensors are mounted on the shaft of the SRM, wherein a

combination of infrared LED (MLED930) and photo

transistor (MRD5009) are used to sense the rotor position

to indicate which of the three phases of the SRM is to be

excited as the motor runs. One of the rotor position

sensor’s output is used to calculate the actual speed of the

SRM. The controller is implemented by software and

executed by an ezDsp F2812 board. The ezDsp kit provides

a complete development environment, and includes the

DSP board, power supply for the board, on-board JTAG

compliant emulator, and an ezDsp specific version of the

Code Composer Studio (CCS) integrated development

environment (full featured, including debugger IDE, and

ANSI C and C++ compliant compiler). The DSP board

itself has nearly all-peripheral signals available on the

board headers, making it easy to interface the board with

other system hardware. The program is completely

contained in the DSP and the computer is only required to

load new programs into the DSP. Additionally, it has an

internal ADC, which can accept up to sixteen analog inputs

and two Event managers, which is used to produce

necessary PWM. Additionally, necessary protection

circuits are used to prevent damage to the DSP. The control

algorithm is written and loaded into the DSP using the PC.

The driver circuit is constructed using totem pole

configuration, wherein NPN (3904) and PNP (2907)

transistors are used. In order to maintain the current at its

rated value, the DC bus current is measured through

current sensor (LEM25-NP). The inputs to the DSP are the

rotor position information and dc bus current. The output

of the switching logic section is a sequence of gating

signals that are pulse width modulated (PWM) gating

signals used to drive the classic bridge converter. The

power converter is a classic bridge converter utilizing six

MOSFETs’ (IRFP360) and fast recovery diodes

(MUR3060). The output of the power converter is a

chopped to get the desired voltage. The complete Block

diagram of the system concept, experimental setup and its

photograph is shown in Fig. 6.

VI. RESULTS

In this section the real time implementation results for

the speed control of SRM drive is presented. In order to

find the performance of different control algorithms, the

following formula is used to find the NRMSE and TRMSE,

wherein (N=100) samples are taken into consideration to

find NRMSE and TRMSE:

\[ N_{RMSE} = \sqrt{\frac{\sum_{k=1}^{N} (N_{ref} - N_{act}(k))^2}{N}} \]  

(19)

\[ T_{RMSE} = \frac{\sum_{k=1}^{N} (T_{desired} - T_{actual}(k))^2}{N} \]  

(20)

where NRMSE is speed root mean square error, TRMSE is

torque root mean square error, Nref is reference speed in

rpm, Tdesired is desired torque, Nact is actual speed in rpm,

Tactual is actual torque, N is no of samples.

Figs. 7-10 show the experimental results of SRM drive at

different operating conditions under soft chopping mode.

Fig. 11 shows the phase voltage and phase current at
different reference speeds after application of load at t=2.5

secs in soft chopping mode. Figs. 7. shows speed response

for reference speed =390 rpm and 40% load is applied to

the shaft of the motor at t=2.5 secs. From the results, it can

be concluded the following.

1. PI controller is more suitable during steady state,

however it is not robust to load disturbance

2. PI type fuzzy controller is more suitable during

transient state to reject the large disturbance, but it has

getting chatter effect during steady state.

3. PD-type fuzzy control suitable for transient state.

\[ \Delta \alpha = N \times \text{actref} - N \times \text{act}(k) \]  

\[ \alpha = \frac{\text{actref}}{\text{act}(k)} \]  

\[ e_{\alpha} = \frac{\text{actref} - \text{act}(k)}{\sum_{k=1}^{N} (N_{ref} - N_{act}(k))^2} \]  

\[ \alpha_{\alpha} = \frac{\sum_{k=1}^{N} (N_{ref} - N_{act}(k))^2}{N} \]  

\[ \alpha_{\mu} = \frac{\sum_{k=1}^{N} (T_{desired} - T_{actual}(k))^2}{N} \]  

(19)

(20)
The controller parameters of PI, PI type fuzzy, PD type fuzzy and STPIFLC algorithms are obtained by conducting the real time experiments of SRM. The parameters of various controllers are tabulated in Table IV. Comparison results are obtained and presented in Table V and VI for different control algorithms from the intensive experiments at different reference speeds, which shows the torque and speed ripples at steady state. As shown in Table V and VII, the presented STPIFLC has the smallest values of N_{RMSE} and T_{RMSE} for various reference speed values. From the experimental results, it is concluded that STPIFLC has smaller N_{RMSE} and hence very low T_{RMSE}. Fig. 12 shows the experimental results of step response with 150 rpm for different controllers. It can be concluded the following observations can be made from these experimental results and are explained. As shown in Fig. 12 (a), the tracking

Since it does not have an integral action, it leads to large overshoot.

4. STPIFLC is more suitable for both transient and steady state. It does not produce overshoot.

Similar results are obtained for other reference speeds as illustrated in Figs. 8-10, using reference speed 750 rpm, 1200 rpm, and 1590 rpm, respectively, as examples.
Fig. 7. Experimental results, speed (top), torque (bottom), 0.4 p.u. load, 390 rpm, (a) PI control, (b) PI-Fuzzy control, (c) PD type fuzzy control, and (d) STPIFLC.

Fig. 8. Experimental results, speed (top), torque (bottom), 0.4 p.u. load, 750 rpm, (a) PI control, (b) PI-Fuzzy control, (c) PD type fuzzy control, and (d) STPIFLC.
Fig. 9. Experimental results, speed (top), torque (bottom), 0.4 p.u. load, 1200 rpm, (a) PI control, (b) PI-Fuzzy control, (c) PD type fuzzy control, and (d) STPIFLC.

Fig. 10. Experimental results, speed (top), torque (bottom), 0.5 p.u. load, 1590 rpm, (a) PI control, (b) PI-Fuzzy control, (c) PD type fuzzy control, and (d) STPIFLC.
performance for conventional PI-control is not good enough due to parameter variations. In contrast, the tracking performance for the controllers other than conventional PI type is satisfied even that the mechanical parameters vary. As shown in Fig. 12 (c) the steady state error for PD-type fuzzy control is still significant for not having integral mechanism. Fig. 13 shows the performance comparison graph for Speed in rpm vs. $T_{\text{RMSE}}$ (p.u.). Comparison results derived from the intensive experimental data can be summarized in Table VII, which shows that the presented STPIFLC is superior to the others regarding to the steady state error, tracking performance and load disturbance rejection.

VII. CONCLUSION

A major issue in the research was the fast tracking capability, less steady state error and robust to load disturbance of the speed control scheme of the SRM drive. The proposed STPIFLC reduces the overshoot as compared...
with PI-type fuzzy logic controller (FLC), while keeping the merits of PI-type FLC. Experimental results prove that the presented STPIFLC for a speed control of SRM drive provides fast tracking capability, less steady state error and robust to load disturbance. To demonstrate the ability of the presented scheme in actual operation of SRM drives, various results were demonstrated. The experimental tests proved that the new control scheme could successfully implement the speed control of the SRM under real operating conditions. It was found that the STPIFLC speed control algorithm is well suited to SRM drives. Apart from this, the merits and demerits of several control approaches are investigated to emphasize the features of the presented STPIFLC. The advantage of designing and implementing the STPIFLC requires a high speed DSP, few logic IC’s and single current sensor.

APPENDIX

Motor Parameters:

- Power: 1.2 kW
- Current: 16 A
- Stator outer diameter: 162 mm
- Stator core length: 90 mm
- Stator inner diameter: 80 mm
- Shaft diameter: 25 mm
- No of poles in the stator: 6
- No of turns/pole: 75
- Cross section of the conductor: 1.7 sq-mm
- Stator pole arc: 29 deg
- Stator pole height: 20 mm
- No of poles in the rotor: 4
- Rotor pole arc: 32 deg
- Rotor Pole height: 15 mm

REFERENCES


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