

# Performance Analysis of Adaptive Fuzzy Logic Controller for Switched Reluctance Motor Drive System

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*Abstract* - This paper presents the application of adaptive fuzzy algorithm for the speed control of switched reluctance motor (SRM). SRM is a highly nonlinear control plant and operates in saturation to maximize the torque output. A systematic approach to the modeling of highly nonlinear SRM drive system which includes the motor, converter, and its electronic controller is presented. Hysteresis current controlled mid-point converter is used to feed a 4KW, four phase, 8/6 pole SRM. Nonlinearity caused by magnetic saturation is accounted for accurate and real-time simulation of drive performance by considering experimental data of magnetization and static torque characteristics. Performance analysis of SRM drive is reported for a wide range of operating conditions viz. starting, reversal and load perturbation dynamics. The performance indices of SRM drive system operating with fuzzy logic controller are compared with the conventional controller to highlight the merits and limitations of fuzzy logic controller.

*Index terms:* Adaptive fuzzy controller, switched reluctance motor, modeling, analysis

## I. INTRODUCTION

The suitability of Switched Reluctance Motor (SRM) for variable speed drive requirements has introduced a reliable, robust and maintenance free workhorse for industrial applications. The relative advantages of SRM drive have made it a front runner, as compared to converter/inverter fed ac/dc drives, for variable speed applications.

The high dynamic performance expected from a variable speed drive includes minimum torque ripple, low steady state error, insensitivity to parameter variation, reduced speed overshoot, fault tolerance, low starting and speed reversal time, and reduced speed oscillations. Such a performance is difficult to be met by conventional controllers as it is required to account for system nonlinearities. Instead of linearizing the plant for specific operating condition and then designing a linear controller, the proposed adaptive fuzzy controller offers an attractive proposition for SRM working under different operating conditions, and motor and load parameter variation.

The electromagnetic torque developed by the motor is a nonlinear function of stator current and rotor position. Hence, attempts have been made to present the dynamic analysis of SRM using different control laws. Feedback linearization control [1,2] has been used in position tracking servo, and direct drive motor for robotic applications [3]. An exhaustive work on feedback linearization control [4] and its comparison with PI [5] control strategy does not present the winding current and torque response. Use of sliding mode controller [6] and its comparison with PI control [7] presents only the mechanical behavior of the motor. Linear model of highly nonlinear SRM is used in variable structure control [8] of SRM. Use of fuzzy control [9] presents the starting and load perturbation response only.

From the available literature it is observed that very few papers

have appeared on the modeling and analysis aspects of control of SRM. The available results are limited in terms of (i) speed, current, and torque response, or (ii) operating point (viz. starting, or sudden application/removal of load torque, or speed reversal), or (iii) parameter variation (moment of inertia, and resistance) is not considered.

To achieve high dynamic performance over a wide range of operating conditions, the application of modern adaptive fuzzy strategy for speed control of SRM drive system is attempted in this paper. Fuzzy set theory provides an effective tool to control the approximate and inexact nature of a real plant. The fuzzy logic control has been experimented to control separately excited dc motors [10] and inverter fed ac motors [11]. A fuzzy logic controller chooses the switching states based on a set of fuzzy variables. Each fuzzy variable (such as motor speed or speed error) is characterized by linguistic expressions such as LARGE, MEDIUM, SMALL in combination with POSITIVE and NEGATIVE. In this paper, the fuzzy speed controller is used to generate the reference current magnitude from the speed error.

This paper, therefore, presents a comprehensive modeling of the drive, and analysis of above stated normal operating conditions, with detailed results of adaptive fuzzy logic based speed control scheme of a four phase, 8/6 pole, 4kV SRM. The current, torque and speed response under all the operating conditions, as also parameter variation are presented. A summary of performance in terms of starting time, dip/rise in speed, overshoot, steady state error in speed, torque pulsations and speed oscillations are reported, and merits and limitations of fuzzy control of SRM are outlined.

## II. SWITCHED RELUCTANCE MOTOR DRIVE

This section describes the control requirements of a typical 8/6 pole SRM shown in Fig. 1(a). It is a four phase machine excited by a mid-point converter (Fig. 1(b)). This converter has only one switching device per phase which reduces the cost, control complexity with no shoot through fault.

Ideal inductance profile of the four phase windings of motor is shown in Fig. 2. In forward motoring, the current in the winding is established for the positive slope region because the motoring torque is developed when  $dL/d\theta$  is positive. The switch is closed by an advance angle  $Q^\wedge$  [12] so that the current rises to the reference current  $I^*$  at the start of the rising inductance of the particular phase. The value of  $Q_m$  is estimated so as to excite the motor winding during rising inductance zone of inductance profile. Else, it may excite during falling inductance zone developing braking torque.

### A. Control Philosophy

The schematic of the closed loop SRM drive system is shown

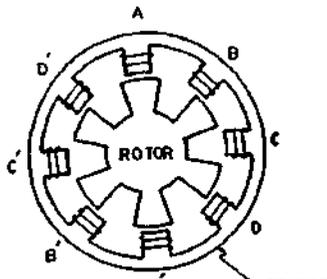


Fig. 1(a) Cross-section of four phase SRM

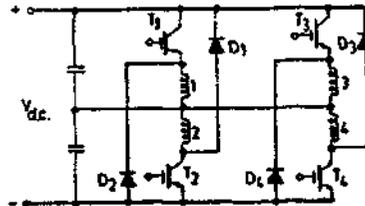


Fig. 1(b) MIU-point converter ID feed power to SRM

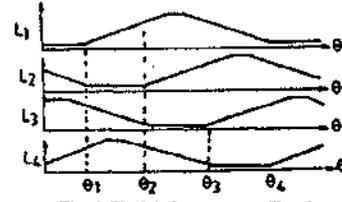


Fig. 2 Ideal inductance profile of four phase SRM  
Sign (+/-)

in Fig. 3. It mainly consists of an outer speed loop comprising four phase motor, position sensor, speed controller and converter. The inner current loop consists of current sensors, reference current generator, current controller and commutation logic. The working of the system is briefly explained here so as to develop its modeling.

Rotor position ( $\theta$ ) is sensed by the position sensor, the derivative of which gives the speed to. The reference speed  $\omega^*$  is compared with the actual speed to. The error signal  $e_{\omega}$  is fed to the fuzzy speed controller. The output of the speed controller is the reference torque  $T^*$  which at any  $n^*$  instant is  $T_{(n)}$ , and is fed to the limiter. The output of the limiter is the reference current magnitude  $I^*$  for all the four phases. Further, the speed signal to decides  $\theta_{on}$  and  $\theta_{off}$  for the fixed  $V_{dc}$ . The signals of reference current magnitude, rotor position  $\theta$  and turn on and turn off angles are fed to the commutation logic block. The commutation logic decides the phase winding to be energized, and the angular duration for which this winding is to be energized, the reference current magnitude  $I^*$  is latched as the reference current, say  $I_1^*$ ,  $I_2^*$ ,  $I_3^*$  or  $I_4^*$  for the corresponding phase winding. The winding current of each phase is sensed at the output of the converter. The current sensor and compared with its reference counterpart in the current controller. The current controller then decides the switching instants (on/off) for the corresponding device of the converter. In response to the sequential controlled excitation of the windings through the converter (and controlled by the controller), the motor drives the load torque  $T_L$ , at the reference speed  $\omega^*$ . Any change of state in the operating condition by way of change in reference speed, load torque, converter voltage etc. is taken care of by appropriate control action generated by the speed controller in close interaction with current controller and commutation logic. The detailed specifications of the motor used in the investigation is given in Appendix I.

### III. MODELING

Different parts of the drive system are modeled separately and integrated to obtain the complete model. The mathematical model of the SRM consists of a set of differential equations obtained using dynamic electric machine theory. The mathematical description of electronic controller includes the modeling of converter, commutation logic, current controller and fuzzy speed controller. The integrated model of the SRM plant, thus, forms the basis for the nonlinear control problem addressed in this paper.

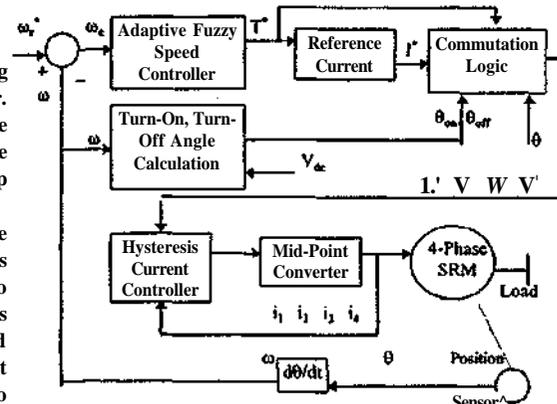


Fig. 3 Schematic diagram of adaptive fuzzy logic based speed control of SRM

#### A. Switched Reluctance Motor

SRM presents a nonlinear control structure since i) it primarily operates in magnetic saturation. ii) the electromagnetic torque developed is a nonlinear function of rotor position and stator currents, and iii) the advance angle and off-angle, which are speed dependent, play a crucial role in developing motoring/braking torque. Hence, in the nonlinear control design [15], it is important to develop a relevant mathematical model which represents the plant dynamics under various operating conditions. Thus, the relevant model equations are:

$$\frac{di_j}{dt} = \frac{1}{L_j} (v_j - i_j r_j) \quad (2)$$

$$\frac{d\theta}{dt} = \omega \quad (3)$$

where  $j$ : 1,2,3,4 represents the phase of SRM

$r$ : winding resistance/phase

$v_j, i_j, \phi_j$ : applied voltage, current and flux-linkage of phase  $j$ .  $T_e$ : electromagnetic torque developed by the motor

$T_L$ : load torque

Due to symmetrical location of poles and magnetic independence of stator windings, the mutual inductance between the phases is neglected,  $\phi_j$  is a nonlinear function of  $i_j$ , and  $\theta$  due to magnetic saturation. Flux-linkage  $\phi_j$  is periodic in nature with period  $2\pi/N$ , and shifted by angle  $\theta_j = (j-1) \cdot 2\pi/N$ ,  $j=1,2,3,4$ . and  $N_r$  is the number of rotor poles.

The physical principles of torque production for doubly salient machines such as SRM are well established. At any rotor position angle, it is possible to produce either positive or negative torque.

The torque developed by phase j is determined by differentiating the coenergy function  $W_c(\theta, i, j)$  with respect to  $\theta$ . i.e.

$$T_j(\theta, i, j) = \frac{dW_c}{d\theta} \quad (4)$$

where

$$W_c(\theta, i, j) = \int \dots \quad (5)$$

The noteworthy characteristics of SRM is that  $T$ , is a nonlinear function of current  $i$ , even if the magnetic circuit is linear. The total torque at any instant is the sum of torques due to all the four phases as given by:

$$T_c = \sum T_j(\theta, i, j) \quad (6)$$

### B. Adaptive Fuzzy Logic Speed Controller

Based on the sliding condition of a conventional sliding mode controller (SMC), an adaptive controller with fuzzy inference is designed for speed control of switched reluctance motor. The fuzzy rule base is used to approximate the equivalent control effort through adaptation, and the sliding mode control effort is used to provide exponential convergence of the sliding variable.

The fuzzy logic speed controller [13,14,15] has the internal structure of a knowledge based expert system. It requires a set of heuristic rules based upon the experience gained in the design of a conventional controller. The rules are expressed in terms of linguistic variables.

The design of fuzzy speed controller is based upon the error inputs  $e$ , and  $e_j$  of conventional SMC structure as given by:

$$e_{j(n)} = \omega_{an1} - \omega_{dn1}$$

where the speed error  $e_{an1}$  at  $n^{\text{th}}$  sampling instant is expressed as:

$$e_{an1} = \omega_{an1} - \omega_{dn1} \quad (8)$$

where  $\omega_{dn1}$  is the speed error at  $(n-1)^{\text{th}}$  sampling instant.

On the speed locus, the switching hyperplane function is expressed in terms of speed error ( $x_{1(n)}$ ) and its derivative ( $\dot{x}_{1(n)}$ ) as follows:

$$z = c_1 x_{1(n)} + c_2 \dot{x}_{1(n)} \quad (9)$$

where,  $c_1$  and  $c_2$  are the switching hyperplane parameters.

In order to avoid the chattering in sliding mode controller, the averaging technique is adopted in the computation of the switching hyperplane function  $z$ . The average value of  $n$  switching hyperplane functions is given by:

$$z = (z_{n1} + z_{n-1} + \dots + z_2 + z_1) / n \quad (10)$$

The functions  $f_1$  and  $f_2$  which decide switching states in the sliding mode controller are expressed as;

$$f_1 = \begin{cases} 1 & \text{if } z > 0 \\ 0 & \text{if } z \leq 0 \end{cases}$$

$$f_2 = \begin{cases} 1 & \text{if } z < 0 \\ 0 & \text{if } z \geq 0 \end{cases} \quad (12)$$

At the  $n^{\text{th}}$  sampling instant the switching functions  $y_{j(n)}$  and  $y_{s(n)}$  take their corresponding values in accordance with the switching law given below:

$$y_{j(n)} = \begin{cases} +1, & \text{if } f_1 = 1 \\ -1, & \text{if } f_1 = 0 \end{cases} \quad (13)$$

$$y_{s(n)} = \begin{cases} +1, & \text{if } f_2 = 1 \\ -1, & \text{if } f_2 = 0 \end{cases} \quad (14)$$

The controller parameters ( $c_1$ , and  $c_2$ ), as given below, are expressed as a function of speed error, acceleration and previous torque command. This ensures convergence of motor dynamics to the set reference operating point.

$$c_1 = F_n \{g, c, x_1, \dots, x_2, \dots, T_{n-1}\} \quad (15)$$

$$c_2 = F_n \{g, c, x_1, \dots, x_2, \dots, T_{n-1}\} \quad (16)$$

where,  $F_n$  is function expressing the left hand side parameters as a function of right hand side variables in eqns. (15) and (16). Here,  $g$ ,  $c$ , are constants and are given in Appendix I.  $c$ , and  $c_2$  are sliding mode controller gains,  $T_{(n-1)}$  is the speed controller output (torque command) at  $(n-1)^{\text{th}}$  sampling instant.

In order to keep track of the previous history of the error and switching strategy, the controller gains  $K$ , and  $K_i$  are defined as:

$$K = c_1 + c_2 x_{1(n)} + c_3 x_{1(n)} \quad (17)$$

$$K_i = c_{i-1} + c_{i-1} x_{1(n)} + c_{i-1} x_{2(n)} \quad (18)$$

The torque command corresponding to speed error is given as:

$$T = K_1 x_{Mn} y_{1(n)} \quad (19)$$

The torque command corresponding to the change in speed error is given as:

$$T = \text{Many} \dots \quad (20)$$

The output of controller at  $11^{\text{th}}$  sampling instant is expressed as:

$$T_{w1} = G_{(n)} T + G_{(n)} \{x_{1(n)} + x_{2(n)}\} + G_{(n)} T_e \{x_{MB} + x_{an}\} \quad (21)$$

where  $G_{(n)}$  and  $G_{(n)}$  are adaptive fuzzy gains depending upon the error and change in error signal. These adaptable gains are obtained by a set of fuzzy rules depending upon the operating range of the physical system in the universe of discourse.

The internal structure of adaptive fuzzy logic controller is shown in Fig. 4. It has three functional blocks for calculation, rule base, database and learning or adaptive law. The functional blocks are i) Fuzzification Interface, ii) Decision Making Logic, and iii) Defuzzification Interface. The functions of the different blocks are briefly described in the following section.

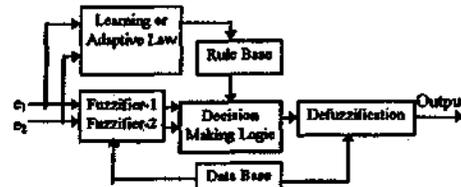


Fig. 4 Internal structure of adaptive fuzzy logic controller

**Fuzzification Interface:** Fuzzy logic makes use of linguistic variables instead of numerical variables. In a closed loop speed control system, the error between the reference speed and actual speed can be termed as zero (Z), positive small (+S), negative large (-L) etc. In real-time system, the measured speed is a real number (or a crisp value). The process of converting this numerical value into a linguistic variable (or a fuzzy number) is called as fuzzification.

**Decision Making Logic:** The conventional SMC controller has two control gains. In case of adaptive fuzzy controller, the equivalent term is the control rules which are linguistic in nature. A typical rule can be written as:

$R_k$ : If  $e$ , is A, AND  $e_2$  is B, then output is C,

where A, B, C, are labels of linguistic variables of  $e$ ,  $e_2$  and output respectively. Fuzzy set theory is used to evaluate the rule table.

Let  $X$  be a collection of objects denoted by  $\{x\}$ , which could be continuous or discrete.  $X$  is called as the Universe of Discourse. If an element in this universe, say  $x$ , is a member of fuzzy set A, then mapping is given as:

$$H(x) \in [0,1]; \quad A = \{x, n(x) | x \in X\}$$

Similar to [16], there is no exact membership function for the output linguistic variables. There are  $m$ -rules to define the rule

base of fuzzy controller and each rule gives a distinct value of the output

*Defuzzification:* The decision making logic provides an output in the form of a fuzzy number. This fuzzy number is transformed to a crisp value as control output by the process of defuzzification. The center of gravity method is used to calculate the final crisp output, as given by:

$$G_{(n)} = \frac{\sum A_i x_i}{\sum A_i} \quad (22)$$

To make the fuzzy control part adaptive in nature, consequent part  $X_k$  is made dependent upon the error ( $e_k$ ) and change in error ( $e_k'$ ) signal, and is obtained through the process of learning [13]. The consequent parameters are adjusted to reduce the sliding function, i.e. the controller is timed to satisfy the sliding condition and consequently have a sliding behavior. The parameters are updated by gradient descent method, using the following learning law [13] for consequent parameters:

$$x_k = \eta z(t) \frac{A_k(t)}{\sum A_k(t)} \quad k=1,2,..,m \quad (23)$$

where  $\eta$  is the learning gain and  $m$  are the total number of rules. *Rule Base:* The rule base stores the linguistic control rules required by the decision making logic. The global set of rule base in adaptive fuzzy control provides two degree of freedom which is of the order of  $7 \times 7$  as shown in Fig. 5.

$e_k$	-Z	-S	-M	-L	-L	-L	-L
-L	+S	-Z	-S	-M	-M	-L	-L
-M	+M	*S	-Z	-S	-S	-M	-L
+S	*M	+M	+S	+Z	-S	-M	-M
Z	+L	+M	+S	+S	+Z	-S	-M
-S	+L	+M	+M	+M	+S	+Z	-S
-M	+L	+L	+L	+L	+M	+S	+Z
-L	-L	-M	-S	Z	+S	+M	+L

Fig. 5 Rule base for global fuzzy set

### Modeling of Converter and Current Controller

This section presents the modeling of the converter feeding power to SRM winding and the current controller which maintains the current through the winding as per reference current magnitude. The switching pattern which controls the switching (on/off) of the converter devices is generated by comparing the winding currents with their reference counterparts. The generated switching pattern is used to appropriately control the gate drive circuit of the converter devices.

1) Converter Modeling: The excitation pattern of the converter devices is governed by the following logic

Phase Current	Device Status	Phase Voltage
For $i_k > 0$	T, On, D <sub>1</sub> Off, D <sub>2</sub> Off	$v_k = VJ2$
	T, Off, D <sub>1</sub> On, D <sub>2</sub> On	$v_k = -VJ2$
For $i_k = 0$	T, Off, D <sub>1</sub> Off, D <sub>2</sub> Off	$v_k = 0$

Similar logic can be written for other converter devices.

2) *Modeling of Hysteresis Current Controller.* In case of a hysteresis current controller, a band is defined around the reference current. The principle of hysteresis current controller is to turn off the device whenever the current through the device exceeds the upper limit of the hysteresis band. Similarly, the

device is turned on whenever the current tends to fall below the lower limit of the hysteresis band. Thus the modeling of switching pattern for turning on or turning off of a particular device is as follows:

$$\begin{aligned} \text{If } i_k < i_k' & \quad \text{Then } T, \text{ ON} \\ \text{If } i_k > (i_k' + hb) & \quad \text{Then } T, \text{ OFF} \\ \text{If } i_k < (i_k' - hb) & \quad \text{Then } T, \text{ ON} \end{aligned} \quad (24)$$

where  $hb$  is the hysteresis band around the reference current  $I_k'$ . Similar switching topology can be written for other winding currents. Thus, the four phase winding currents are regulated in magnitude as per their reference current magnitudes.

3) *Commutation Logic:* As explained earlier, the winding current is to be established in the rising zone of inductance profile for motoring torque and falling inductance zone for braking torque. The process of excitation is started by an advance angle  $\theta_{cl}$  [12] such that the winding current rises to the reference current  $I_k'$  at the start of the rising inductance region of the particular phase. The value of  $\theta_{cl}$  is given by

$$\theta_{cl} = \arcsin \left( \frac{I_k' L}{V_{dc}} \right)$$

Similarly  $\theta_{ex}$  is calculated as a fixed percentage of  $\theta_{cl}$ . In the present investigation, the value of  $\theta_{cl}$  has been taken as 15% of  $\theta_{cl}$ , i.e.

$$\theta_{ex} = 0.15 \theta_{cl} \quad (26)$$

The excitation and extinction of a particular phase winding is dependent upon the current rotor position  $\theta$ ,  $\theta_{cl}$ , and  $\theta_{ex}$ . With reference to Fig. 2 of ideal inductance profile.

Let  $\theta_{cl} = \theta_{cl} + \theta_{ex}$ ,  $\theta_{ex} = \theta_{cl} - \theta_{ex}$ , then

$$\begin{aligned} \text{If } \theta_{cl} < \theta < \theta_{ex} & \quad \text{Then Excite Phase-1} \\ \text{If } \theta_{ex} < \theta < \theta_{cl} & \quad \text{Then Excite Phase-2} \\ \text{If } \theta_{cl} < \theta < \theta_{ex} & \quad \text{Then Excite Phase-3} \\ \text{If } \theta_{ex} < \theta < \theta_{cl} & \quad \text{Then Excite Phase-4} \end{aligned} \quad (27)$$

For forward motion, the winding excitation sequence is 1-2-3-4-1 whereas the reversal of direction of rotation is achieved by exciting the winding in 4-3-2-1-4.

The braking torque is produced by exciting the winding in the falling zone of inductance profile. This is achieved by advancing the current rotor position  $\theta$  by stator pole arc  $p$ .

The motor speed is maintained constant at reference speed by the following logic:

If  $\omega > \omega_r$ : Excite the winding in falling inductance zone (i.e. if the motor speed exceeds the reference speed, decelerate the motor, apply braking torque, excite the winding in falling inductance zone).

If  $\omega < \omega_r$ : Excite the winding in rising inductance zone (i.e. if the motor speed is below the reference speed, accelerate the motor, apply motoring torque, excite the winding in rising inductance zone).

With the modeling of the commutation logic, the individual parts of the SRM drive system have been separately explained and modeled. The above described mathematical equations which govern the dynamic behavior of SRM, form the basis of integrated model of the complete drive system.

## IV. SIMULATION

Simulation of integrated mathematical model described in the previous section is carried out to compute the performance parameters of the SRM drive system. A simulation algorithm is developed which makes use of the above differential equations.

excitation conditions, switching pattern, commutation logic and machine experimental data. The family of magnetization curves and static torque characteristics used in the performance analysis are given in Appendix II.

In the software developed to simulate the evolved modeling strategy, there is a main program and five subroutines as shown in Fig. 6. The main program calls the different subroutines, and at every iteration it adapts the fuzzy controller gain parameters. The six differential eqns. to compute the motor speed, and rotor position, and flux linkages of four phase windings, are integrated using modified fourth order Runge-Kutta-Vernier method in the Runge subroutine. This Ruiige subroutine is supported by four subroutines-Function, Volt, Amp and Torq. 'Function' provides the derivative of flux linkage, speed and rotor position to 'Runge'. 'Volt' decides/computes the voltage required to be applied across the winding. 'Amp' interpolates the currents for all the four phases from the experimental magnetization curve data. For the present rotor position ( $\theta$ ) and current obtained from 'Amp', the value of developed instantaneous electromagnetic torque is interpolated from experimental static torque curve data from 'Torq'. The values of speed, torque, flux-linkage, current and voltage are stored to analyze the dynamic response and performance of the drive system under different operating conditions.

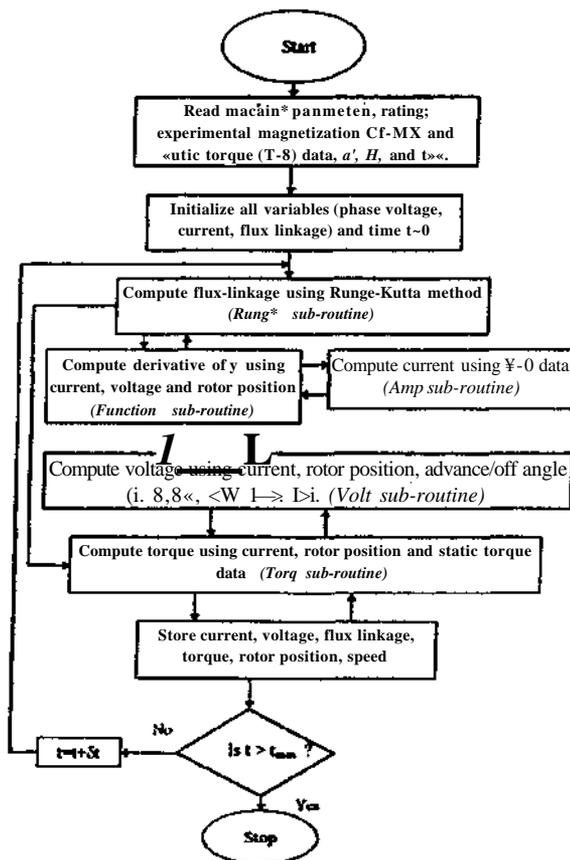


Fig. 6 Flowchart of the algorithm developed for speed control of SRM

## V. RESULTS AND DISCUSSION

Using the algorithm developed in the previous section, the dynamic performance of the drive system is simulated for different operating conditions such as i) Starting, ii) Speed reversal, and iii) Load torque disturbance.

The effectiveness of the fuzzy speed controller is evaluated in terms of

- i) Time required by the motor to accelerate from rest to reach steady state at reference speed (starting time),
- ii) Time taken by the motor rotating at steady state speed in one direction to reach steady state rotation in reverse direction for speed reversal (reversal time)
- iii) Dip/Rise in speed on sudden change of load torque.
- iv) Overshoot and steady state error in speed
- v) Speed ripple (difference in peak to peak value at steady state speed)
- vi) Torque ripple

*1) Starting Response:* The starting response of SRM operating with adaptive fuzzy controller in speed loop is shown in Fig. 7. With the motor at rest, the reference speed is set at 1500 r/min. Within 25 msec the motor speed reaches the set speed of 1500 r/min without any overshoot and zero steady state error in the speed (Fig. 7(a)). During starting, there is a change in state and hence motor requires large energy and large torque. Hence, during starting the motor draws large current limited by the limiter to a value of 28.0 A peak, so as to accelerate and reach the reference speed. On reaching the reference speed, the current drawn by the motor reduces to 4.5 A peak and corresponds to the load driven by the motor. The current drawn by all the four phase windings is shown in Fig. 7(b) and the torque developed by the four phases is shown in Fig. 7(c). The net torque developed by the motor during starting is limited to a value of 65 Nm, corresponding to the limit set by the reference current, and is shown in Fig. 7a(iii). During steady state, the peak torque value developed by the motor oscillates between a maximum of 3.5 and a minimum 0.5 Nm with an average value of 2 Nm corresponding to the no load torque experienced by the motor. The large amount of energy required during starting and small amount of energy required to maintain the steady state speed at 1500 r/min at no load can be observed by Fig. 7(aiv), which shows the area under the curve of flux-linkage vs current during starting and steady state. The voltage pattern appearing across the motor winding (for one phase) is shown in Fig. 7a(ii). The voltage across other phases are similar with time displacement.

Since, there are four phase windings, in further results, current of one phase and the torque developed by that phase only will be presented. The current and torque response of all other phases is similar with time displacement.

*2) Speed Reversal Response:* The dynamic response of SRM drive operation under speed reversal is shown in Fig. 8. Initially the motor is rotating at a speed of +1500 r/min under steady state. At time  $t=0.1$  sec, the command for speed reversal is issued to the motor. Within 90 msec, the direction of rotation of the motor is reversed. During transition of motor direction from +1500 r/min to -1500 r/min, the controller output is saturated and a large current (Fig. 8(b)) is demanded by the motor to develop a large

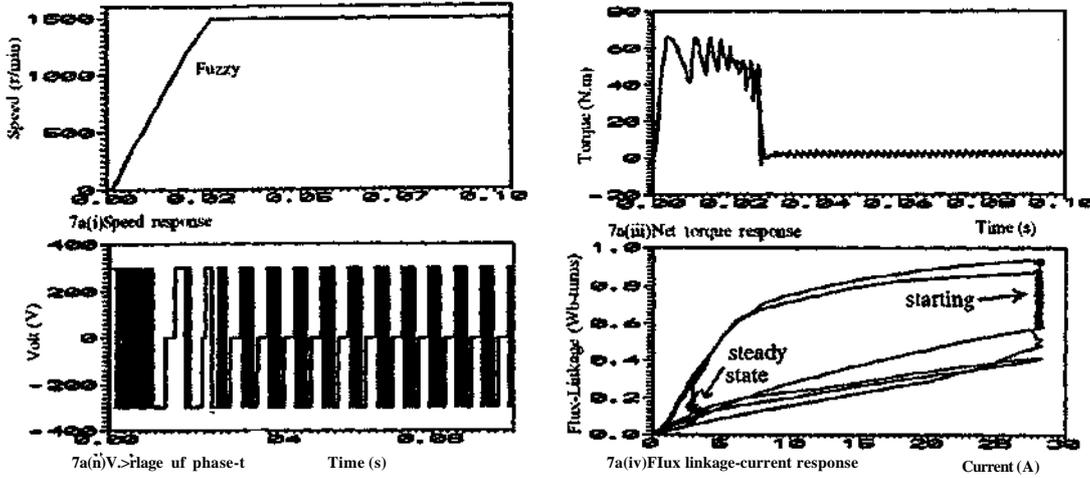


Fig. 7(a) Speed, voltage, net torque and flux-linkage during starting of SRM

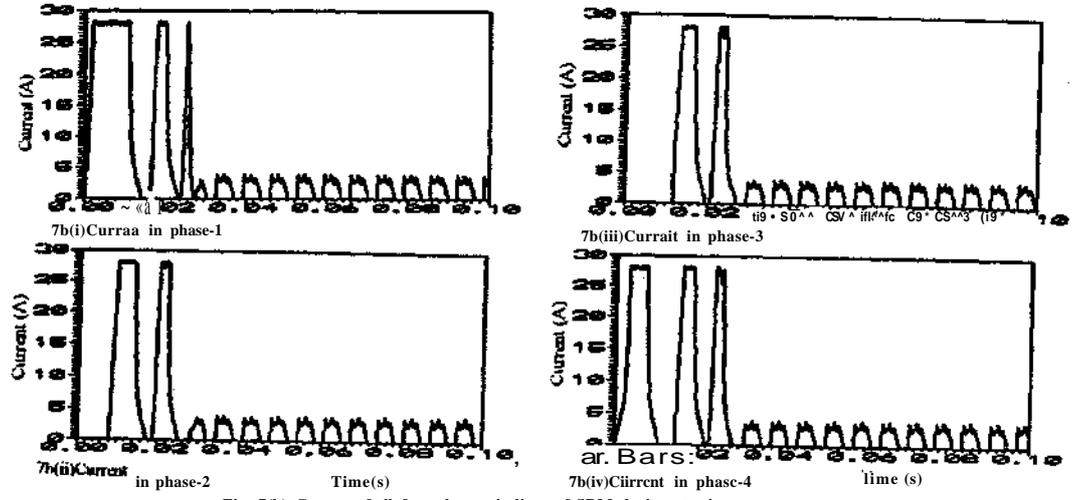


Fig. 7(b) Current of all four phase windings of SRM during starting

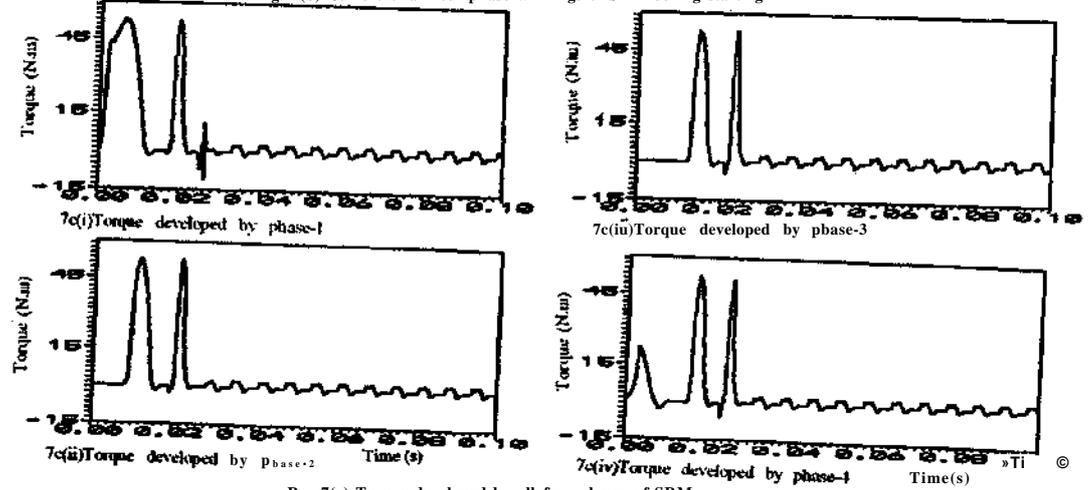


Fig. 7(c) Torque developed by all four phases of SRM

Fig. 7 Response of SRM during starting

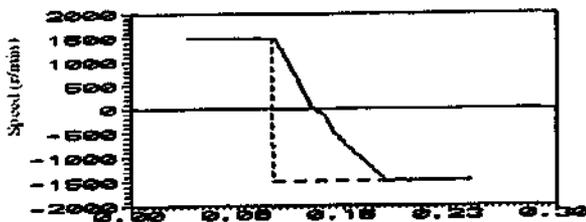


Fig. 8(a) Speed response



Fig. 8(c) Torque developed by Phase-1

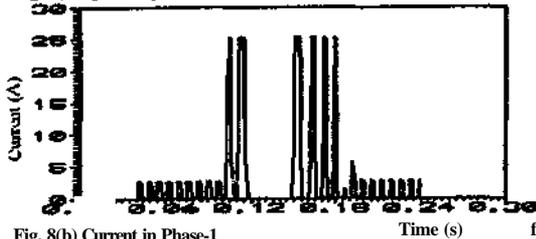


Fig. 8(b) Current in Phase-1

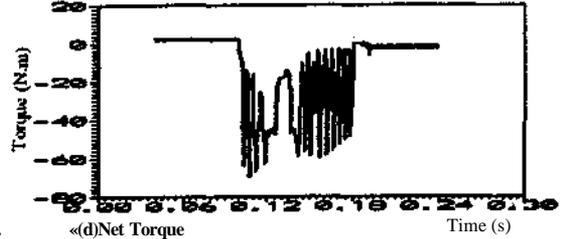


Fig. 8(d) Net Torque

Fig. 8 Response of SRM (during speed reversal)

torque (Fig. 8(c), 8(d)) so as to effect the reversal of direction of rotation. As soon as the reversal of direction is achieved, the motor rotates at the new steady state speed of -1500r/min and the transients in current and torque vanish. The new values of current and torque correspond to the new operating point as shown in Fig. 8(b), 8(c).

3) *Load Torque Disturbance:* The response of SRM drive on sudden application of full load torque on the motor operating at no load or sudden removal of full load torque is presented in this section. The response of sudden application/removal of load torque on motor performance is shown in Fig. 9. Initially the motor is running at no load torque of 2 Nm at steady state speed of 1500 r/min. Due to inherent nonlinear characteristics of SRM the speed ripple is 1 r/min. At time  $t=0.08$  sec, the full load torque is suddenly applied to the motor shaft. Due to this sudden application of full load torque, the rotor experiences a dip of 30 r/min in speed and the developed electromagnetic torque quickly jumps to the new value corresponding to the full load torque (25 Nm) on motor shaft. The speed, winding current, per phase torque and net torque response are shown in Fig. 9(a), 9(b), 9(c) and 9(d). The sudden removal of full load torque at  $t=0.14$  sec, results in a small rise in speed of 2 r/min. However, the fuzzy logic controller comes into action and the motor is able to gain control on machine dynamics. Thus, the drive exhibits superior load bearing capability using fuzzy logic speed controller. The torque ripple on full load is 12 N.m (31-19 N.m) and the speed ripple is 5 rpm (1485-1480 rpm).

In the results presented above, the corresponding speed response of the motor using conventional sliding mode controller is also presented to facilitate the comparison of drive performance using the two different controllers.

4) *Parameter Sensitivity Test:* The results of the parameter sensitivity test is carried out by varying the moment of inertia ( $J$ ) and winding resistance ( $r$ ), and the results are shown in Fig. 10. During Steady State operation at nominal moment of inertia ( $J$ ), a change in  $J$  is experienced at  $t=60$  ms, wherein the value of  $J$  is increased by two times. The speed response of SRM for this

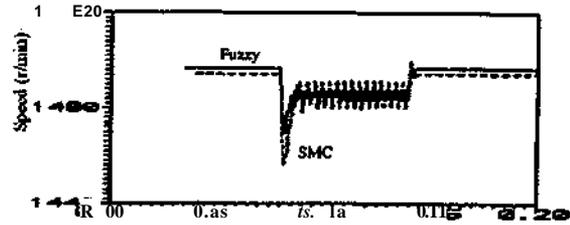


Fig. 9(a) Speed response

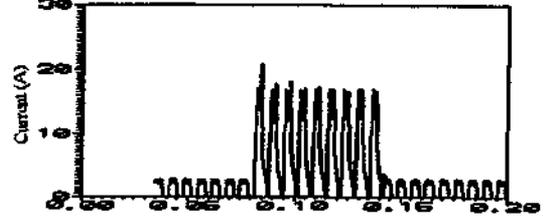


Fig. 9(b) Current in Phase-1

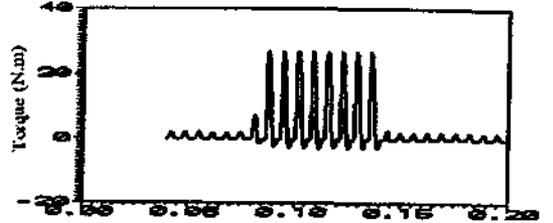


Fig. 9(c) Torque developed by Phase-1

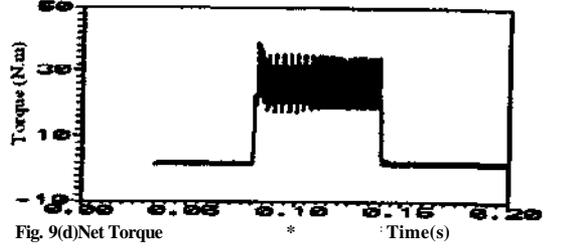


Fig. 9(d) Net Torque

Fig. 9 Response of SRM during load torque disturbance

change in  $J$ , experienced by the drive system, is shown in Fig. 10(a). It can be observed that the doubling of moment of inertia, results in reduction in the steady state speed ripple. Similarly, while steady state operation at nominal winding resistance, a change in resistance is experienced at  $t=60$  ms, wherein the value of  $V$  is increased by five times. The speed response of SRM for this change experienced by the drive system is shown in Fig. 10(b). Since the motor operates in saturation, any change in winding resistance has negligible effect on the current drawn by the motor and hence the operating speed. From Fig. 10, it is observed that the proposed system operates satisfactorily for parameter variations, without any major disturbance to the drive operation.

A summary of drive performance is presented in Table-1, which gives the starting time, steady state error in speed, reversal time, speed ripple and torque ripple of the fuzzy logic based control of switched reluctance motor. Corresponding values using conventional SMC controller, are also given in the table for performance comparison.

Table-1: Performance comparison of fuzzy logic controller with conventional sliding mode controller (SMC)

Controller	SMC	Fuzzy
Starting time (ms)	35	25
Steady state error (r/min)	23	15
Reversal time (ms)	100	90
Dip in speed on application of full load (r/min)	1500-1455 -45	1500-1470 -30
Rise in speed on removal of full load (r/min)	5	2
Speed ripple (r/min)	1492-1480 -12	1485-1480 =5
Torque ripple (N.m)	35-18=17	31-19-12

## VI. CONCLUSIONS

The paper demonstrates the versatile application of fuzzy logic theory for simulation and control of SRM drive system. A relevant comprehensive model of the motor, converter and control logic is developed which is adaptable to fuzzy and other control algorithms. The motor has been modeled through measured characteristics for different 9. Commutation strategy and converter modeling involves relevant switching logic. Control algorithm involves processing of feedback signals of rotor position, speed and winding currents in comparison with reference signals, incorporating fuzzy model.

The effectiveness of the model has been established by performance prediction of SRM over a wide range of operating conditions including starting, speed reversal, load perturbation and parameter variation. The feasibility of using high performance adaptive fuzzy logic speed controller for SRM drive has been illustrated. It has been found that the proposed speed controller offers its own advantages and limitations. On the positive side, the controller adds intelligence to the control action in terms of quick response and load bearing capability. Also, in adaptive fuzzy

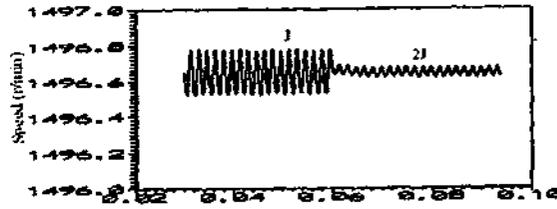


Fig. 10(a) Speed response of SRM under variation of moment of inertia

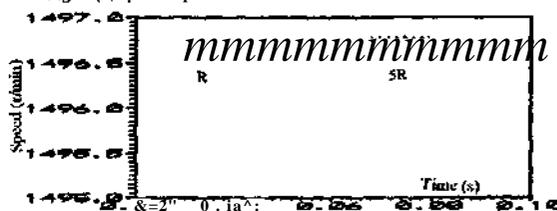


Fig. 10(b) Speed response of SRM under variation of winding resistance

Fig. 10 Parameter sensitivity testing i if SRM

control, the gain scheduling of control parameters is not required, for any change in operating point, which is in contrast to sliding mode, feedback linearization or PID control strategy. Torque ripple and speed ripple are inherent characteristics of SRM but have been kept well within permissible limits as observed by the response of the drive. The main limitations of any fuzzy control are i) the real-time implementation of fuzzy controller has to be considered from techno-logical constraints such as discrete-time implementation and requirements of high speed PWM switching converter. ii) lack of systematic procedure for design and analysis of the control plant which is currently being performed by a time consuming trial-and-error iterative approach, iii) there is no definite criteria for selection of the shape of membership functions, degree of overlapping of the subsets and levels of quantization, iv) incompleteness in rule base to give a meaningful control action for every condition of the process.

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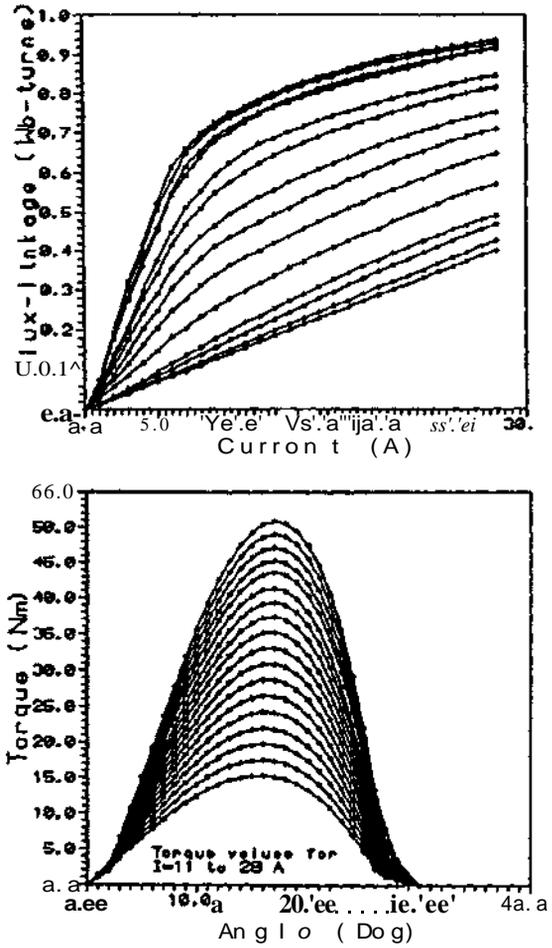
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Experimental flux-linkage and static torque characteristics used in the analysis



Appendix-I

- Motor specifications:
- Power=4kW, Speed=1500 rpm. No. of Phase=4
  - DC link voltage=600V, Peak current=28A
  - Stator poles=8. Rotor poles=6
  - Stator winding resistance=0.72 ohms
  - Aligned inductance=10 inH
  - Unaligned inductance=150 mH
  - Moment of Inertia J=0.008 Kg-m<sup>2</sup>
  - Switching hyperplane coefficients
  - c<sub>1</sub>=8.875      c<sub>2</sub>=0.98
  - Sliding mode controller gains
  - c<sub>3</sub>=8.5      c<sub>4</sub>=5.6
  - g<sub>1</sub>=0.0068      g<sub>2</sub>=0.293
  - Learning constant
  - r<sub>1</sub>=0.5