

## **FUZZY BASED FAULT DETECTION AND CONTROL FOR 6/4 SWITCHED RELUCTANCE MOTOR**

N. SELVAGANESAN, D. RAJA AND S. SRINIVASAN

**ABSTRACT.** Prompt detection and diagnosis of faults in industrial systems are essential to minimize the production losses, increase the safety of the operator and the equipment. Several techniques are available in the literature to achieve these objectives. This paper presents fuzzy based control and fault detection for a 6/4 switched reluctance motor. The fuzzy logic control performs like a classical proportional plus integral control, giving the current reference variation based on speed error and its change. Also, the fuzzy inference system is created and rule base are evaluated relating the parameters to the type of the faults. These rules are fired for specific changes in system parameters and the faults are diagnosed. The feasibility of fuzzy based fault diagnosis and control scheme is demonstrated by applying it to a simulated system.

### **1. Introduction**

The Switched Reluctance (SR) motors have undergone rapid development in hybrid electric vehicles, aircraft starter/generator systems, washing machines, and automotive applications over the last two decades. This is mainly due to the various advantages of SR motors over other electric motors such as structural simplicity, high reliability and low cost [5]. Many papers have been presented in design and control [6,7, 9, 11] of SR motor, where speed and torque are required.

To obtain the model for control and optimization of the drive, a precise mathematical model is necessary, where the magnetic characteristic of the SR motor is a nonlinear function of phase current and rotor position. Obtaining the mathematical model is not an easy task, because the magnetic circuit operates at varying levels of saturation under operating conditions. To reduce the complexity, the linearized model [12] is used for design and performance analysis of the controller.

A number of approaches have been proposed in recent years for the detection and diagnosis of failures in dynamic systems. Powerful and at the same time, operator oriented supervision concepts are in demand in the industry now. Model based fault diagnosis concept, is an approach which has increasingly gained attention over the last decade due to the demand for uninterrupted operation, higher safety

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and reliability standards. The discussion on the fault-tolerance of SR motors in the published literature has mostly been on the conceptual level without any detailed analysis. It has been reported [13] that the detection and management of SR motor faults fails to provide an analytical tool to quickly analyze and predict the performance under faulted conditions. Most of the results presented were machine specific and not general enough to be applicable as an evaluation tool. A finite element approach is presented which is extremely time consuming [1] and a generalized method for predicting the post-fault performance is presented in [2].

This paper deals with fuzzy based fault detection and control of a SR motor. A Fuzzy Logic Controller (FLC) [3, 4, 8, 10] is designed and its performance is compared with the conventional Proportional plus Integral (PI) controller. Also, a fuzzy logic system is created for fault diagnosis purposes. This concept of fault diagnosis consists of two steps. First, the parameters which reflect faults in the process behavior are measured. In the second step, a decision is made by determining the type of faults from the change in parameters. Various faults are simulated in the MATLAB environment and the results are presented in this paper.

The rest of the paper is divided into four sections. The SR motor modeling is dealt in Section 2. The fuzzy controller design is presented in Section 3. In Section 4 the fault diagnosis concept and its simulation using fuzzy logic is explained. We conclude with Section 5.

## 2. SR Motor Drive

A 3- $\phi$  6/4 SR motor [9, 12], 2-switch per phase bridge converter topology with PI / FLC speed controller is chosen. A control block diagram of this drive system is shown in Figure 1. The controller has an inner current control loop and an outer speed control loop. The speed controller generates a current command based on the error between the reference speed and the motor speed. The current in the designated phase is regulated at the reference level by hysteresis control.

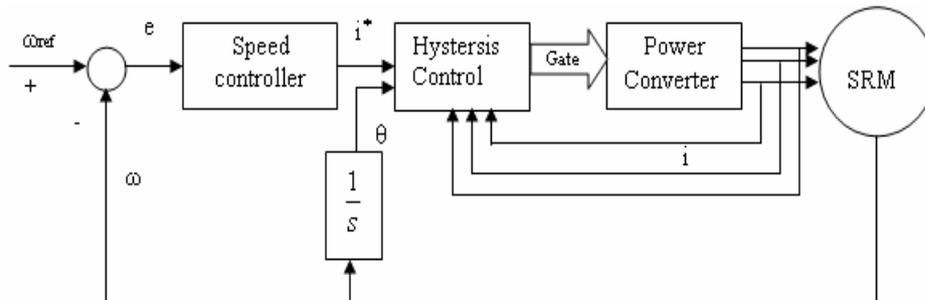


FIGURE 1. Block diagram of the SR motor drive.

**2.1. SR Motor Modeling.** The SR motor model considered has six poles on the stator and four on the rotor [9, 12]. The instantaneous voltage of a SR motor across

the terminals of a phase winding is related by Faraday's law to the flux linked in the winding is as follows:

$$V = RI + \frac{d\Psi}{dt} \quad (1)$$

where,  $V$  is terminal voltage

$I$  is phase current

$R$  is phase winding Resistance

$\Psi$  is flux linked by the windings

Due to the doubly salient structure, the variation in the flux linked to a phase varies as a function of rotor position  $\theta$  and phase current  $I$ , (1) and can be expanded as,

$$V = RI + \frac{\partial\Psi}{\partial I} \frac{dI}{dt} + \frac{\partial\Psi}{\partial\theta} \frac{d\theta}{dt} \quad (2)$$

where  $\frac{\partial\Psi}{\partial I}$  is defined as  $L(I,\theta)$ , the instantaneous inductance and term  $\frac{\partial\Psi}{\partial\theta} \frac{d\theta}{dt}$  is the instantaneous back e.m.f.

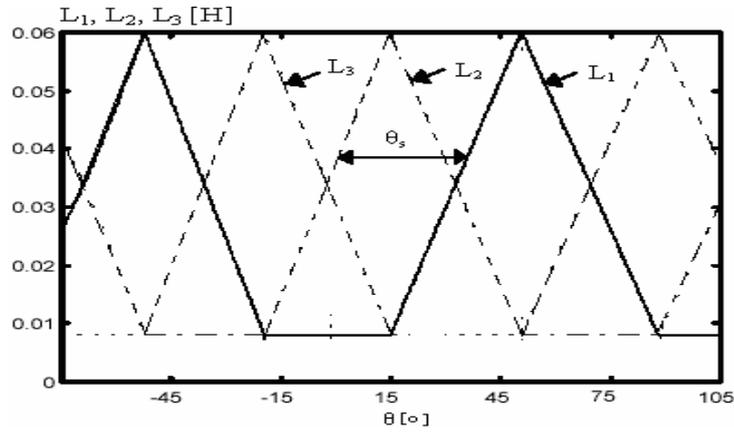


FIGURE 2. Linear inductance profile of each phase for SR motor

Figure 2 shows the linear inductance profile of  $L(\theta)$ ; each phase inductance is displaced by an angle  $\theta_s$  is given by

$$\theta_s = 2\pi \left( \frac{1}{N_r} - \frac{1}{N_s} \right) \quad (3)$$

where  $N_r$  and  $N_s$  are the number of rotor and stator poles respectively. While excluding the saturation and mutual inductance effects, the flux in each phase is given by

$$d\Psi_i(\theta, I_i) = L(\theta) \cdot I_i \quad (4)$$

where  $i$  is the phase ( $i = 1, 2, 3$ ). The total energy associated with the three phases is,

$$W_{\text{total}} = \frac{1}{2} \sum_{i=1}^3 L(\theta + (n-i-1)\theta_s) I_i^2 \quad (5)$$

The total torque developed by the motor is given by

$$T = \frac{1}{2} \sum_{i=1}^3 \frac{dL(\theta + (n-i-1)\theta_s)}{d\theta} I_i^2 \quad (6)$$

and the mechanical equations are given by

$$J \frac{d\omega}{dt} = T - T_L - f\omega \quad \text{and} \quad \frac{d\theta}{dt} = \omega \quad (7)$$

where,  $J$  is moment of inertia

$T_L$  is load torque

$f$  is the friction coefficient.

### 3. Design of Fuzzy Logic Controller

The typical block diagram of the FLC with process is shown in Figure 3. The design of the fuzzy logic controller [3, 4, 10] is as follows.

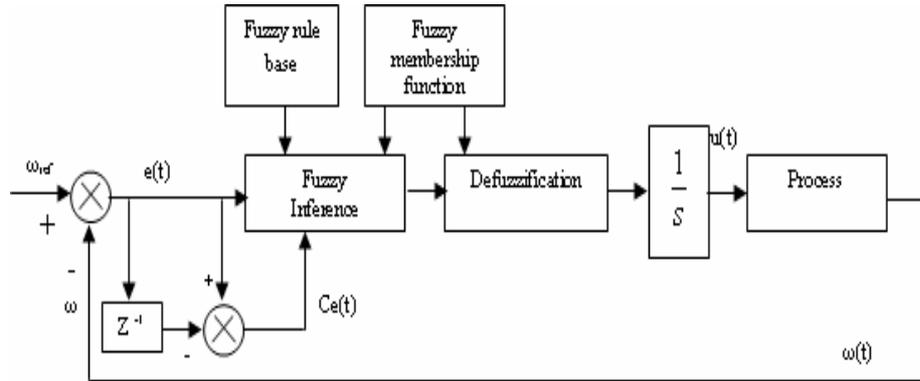


FIGURE 3. Block diagram of the FLC System

The input variables used for the FLC are the error  $e(t)$ , i.e. the difference between the desired speed and the measured value of speed, and the change in error  $\Delta e(t)$ , i.e. the difference between the error at the present instant  $e(t)$  and the error at the previous instant  $e(t-1)$ . The output variable is the change in output  $\Delta u(t)$  and the output of the FLC is given by

$$u(t) = u(t-1) - \Delta u(t) \quad (8)$$

The universe of discourse for error is set as  $-4$  rad/sec to  $4$  rad/sec, for change in error is  $-2$  rad/sec to  $2$  rad/sec and for change in output  $-50$  A to  $50$  A, over the speed range from  $80$  rad/sec to  $160$  rad/sec. The fuzzy memberships are chosen based on the response of the conventional controller. To improve the controller performance the membership functions are further adjusted based on trial and error procedure.

The fuzzy input and output variables, namely error, change in error and change in output, are given in Figure 4 with subplots (a, b, c), each of which is divided into seven linguistic variables, namely NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). Unequal width triangular membership function along with 'Z' and 'S' membership functions are used to construct FLC block.

To maintain the speed at desired level for the given operating condition, the triangular membership is cramped near zero. This is mainly due to the variation in inductance which affects the control variable (speed) and hence a change in the shape of the membership function is required. The membership function of Z, PS and NS of the FLC will be cramped near zero and expanded for NM and PM.

The symmetrical S and Z functions are considered for NB and PB respectively. The Z and S membership functions are chosen instead of triangular membership functions in order to have smooth transition during the transient period. The rules that tie the input and output variables are given in Table 1. The max-min implication technique is used for decision making and the 'center of area' method is used as a defuzzifier which generates the center of gravity of the final fuzzy control space.

$\Delta e$ e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Table 1. Shows the rule database

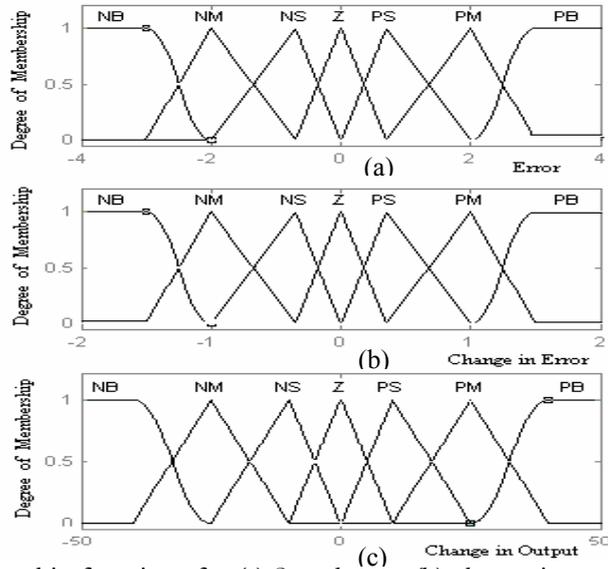


FIGURE 4. Membership functions for (a) Speed error (b) change in speed error(c) Change in output

#### 4. Results and Discussion

**4.1. FLC Simulation.** The parameters of the PI controller are chosen by trial and error as  $K_p = 11.8$ , and  $T_i = 1.45$  seconds. The control performance of FLC is simulated with change in reference speed (servo response) and load disturbance (regulatory response). Using the designed fuzzy controller, the performance of the FLC is compared with conventional PI controller based on the Integral Absolute Error (IAE) and Integral of Time weighted Absolute Error (ITAE).

$$IAE = \int |e| dt, ITAE = \int t|e| dt \quad (9)$$

IAE mainly accounts for the error at the beginning of the response and to a lower degree during the steady state deviation. ITAE takes account for both transient and steady state error.

**4.1.1 Servo Response.** The set point is initially varied from 120 rad/sec to 140 rad/sec at  $t = 0.2$  sec and from 140 rad/sec to 130 rad/sec at  $t = 0.4$  sec. The response of the PI controller and FLC are shown in Figure 5.

**4.1.2 Regulatory Response.** For a given set point of 120 rad/sec, load disturbance is simulated by varying the load torque. At  $t = 0.2$  sec, the load torque is increased by 25 % of its rated value and at  $t = 0.4$  sec, the influence torque is decreased by 50%. The response of the PI controller and FLC are shown in Figure 6. The servo and regulatory response demonstrate the comparable steady state performance, where the FLC are slightly better than the PI controller. The quantity

results summarized in Table 2 confirm that FLC achieves a better transient performance than a PI controller.

CONTROLLER TYPE	Servo		Regulatory	
	IAE	ITAE	IAE	ITAE
PI	1.882	0.1628	1.94	0.1916
FLC	1.788	0.1396	1.902	0.1881

Table 2. IAE and ITAE

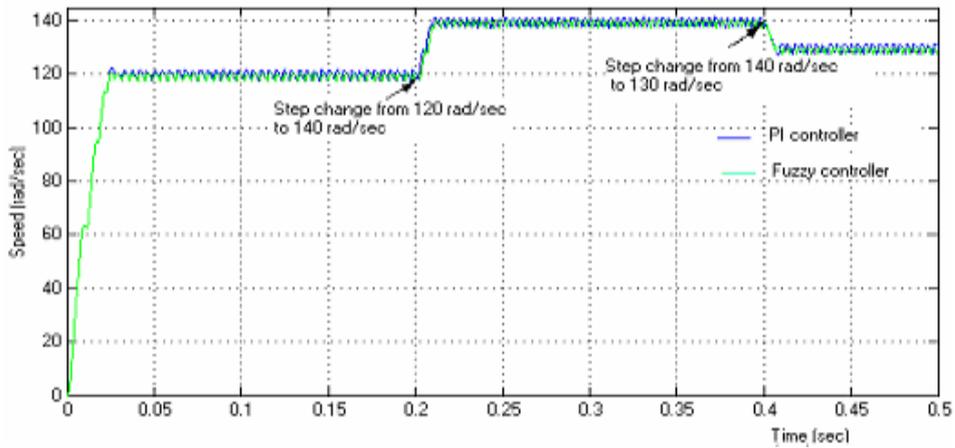


FIGURE 5. Servo response of controllers

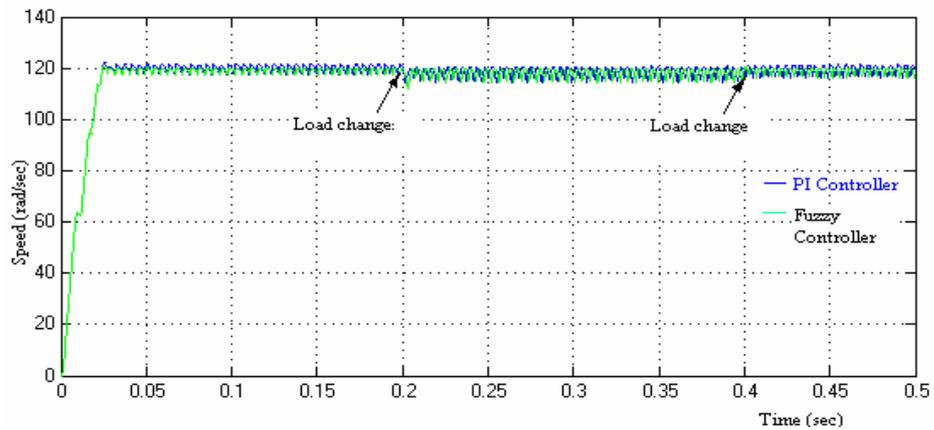


FIGURE 6. Regulatory response of controllers

**4.2. Faults Simulation.** The fault identification for the SR motor is done offline. Faults that usually occur in a SR motor are the one phase open circuit fault, the two phase open circuit fault, the phase to ground fault and the locked rotor fault.

**4.2.1 One Phase Open Circuit Fault.** This situation occurs when any two of the three phases are open. This results in a zero current in the corresponding phase and there is no further contribution of torque production from that phase. This condition is simulated by opening a phase at 0.3 Sec and the corresponding speed, torque and current responses are plotted as shown in Figures 7 to 9.

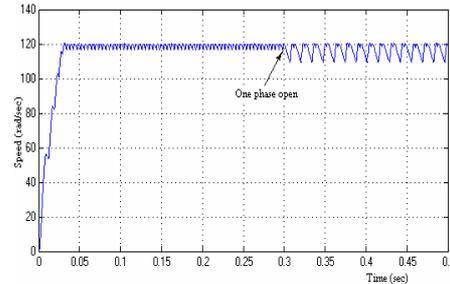


FIGURE 7. Speed response due to one phase open

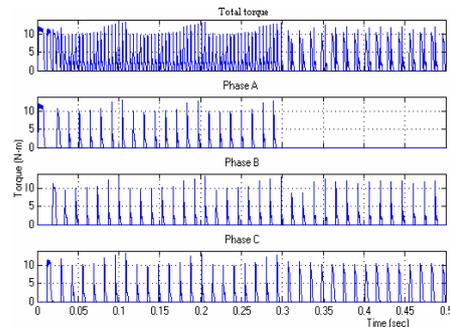


FIGURE 8. Torque response due to one phase open

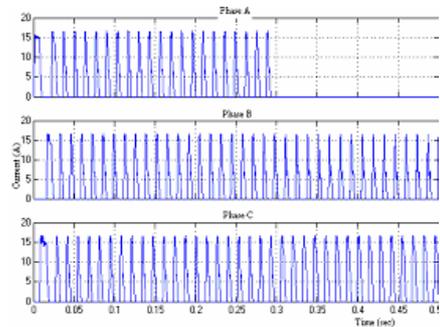


FIGURE 9. Individual phase current responses due to one phase open

**4.2.2 Two Phase Open Circuit Fault.** This situation occurs when any two of the three phases are open. This results in a zero current in the two open phases and there is no further contribution of torque production from these phases. This

condition is simulated by opening two phases at 0.3 Sec. Figures 10 and 11 show the speed and torque responses and Figure 12 shows the current response.

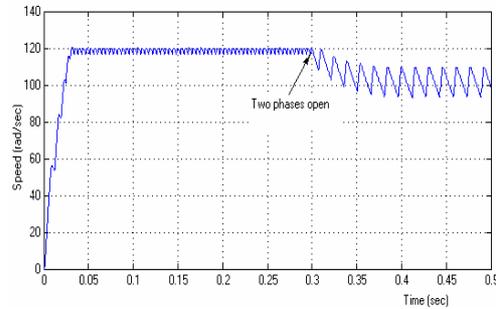


FIGURE 10. Speed response due to two phase open

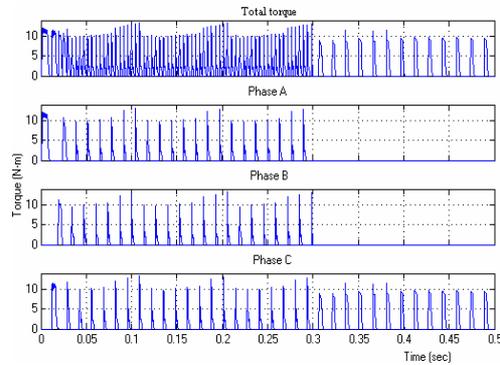


FIGURE 11. Torque response due to two phases open

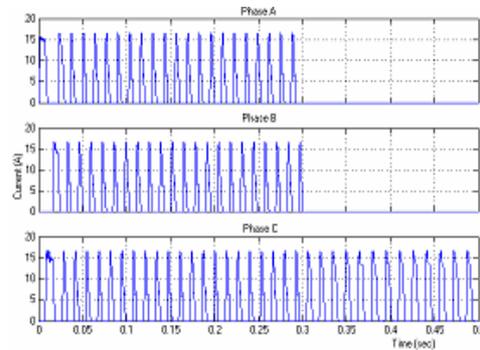


FIGURE 12. Individual phase current response due to two phases open

**4.2.3 Phase to Ground Fault.** This situation occurs when any one of the phase windings is short circuited to a grounded component such as stator core. This results in an over current in that phase. This condition is simulated by increasing

phase current at 0.3 sec. Figures 13 and 14 show the speed and torque responses and Figure 15 shows the current response.

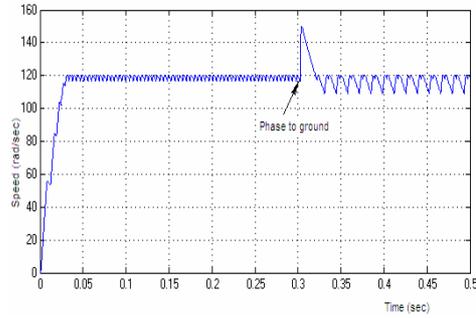


FIGURE 13. Speed response due to phase to ground fault

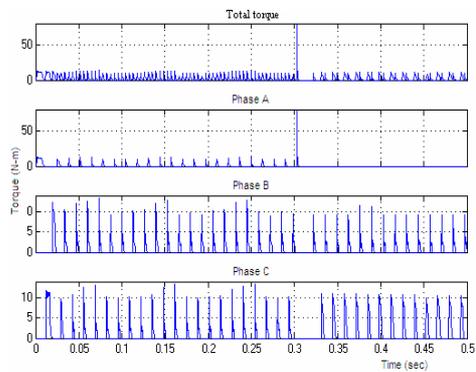


FIGURE 14. Phase torque response due to phase to ground fault

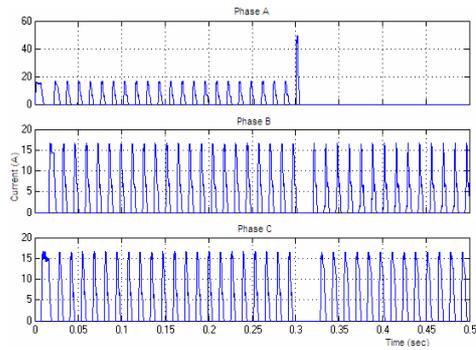


FIGURE 15. Individual phase current response due to phase to ground fault

**4.2.4 Locked Rotor.** The prevented rotation or obstruction of rotor may be termed as a locked rotor condition which occurs due to mechanical reasons. This condition is simulated by applying almost 400% to 500% of normal operating

torque. This condition can be tolerated only for a limited time. The motor should be switched off immediately. The corresponding speed, torque and current responses are shown in Figure 16 to 18.

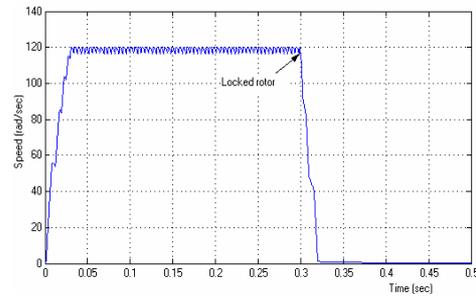


FIGURE 16. Speed response due to locked rotor

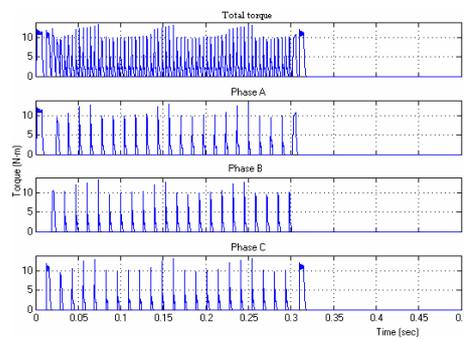


FIGURE 17. Torque responses due to locked rotor

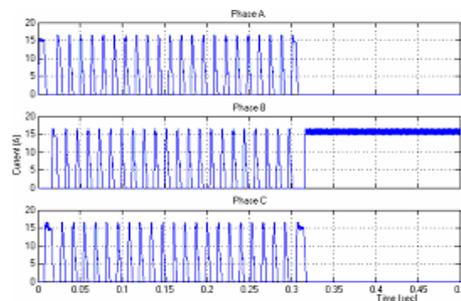


FIGURE 18. Individual phase current response due to locked rotor

**4.3. Fuzzy Based Fault Diagnosis.** The proposed model based fuzzy fault diagnosis system consists of three basic steps, namely parameter generation, parameter evaluation and fault presentation.

**4.3.1 Parameter Generation.** The mathematical model of the system is used to generate the parameters like speed, torque and three phase currents for normal and

faulty conditions. These parameters are affected by every specified fault which is given as the input to the fuzzy system.

**4.3.2 Fuzzy Based Parameter Evaluation and Fault Presentation.** The range of membership functions for the input and output parameters are shown in Figure 19. The trapezoidal membership function, with variable width, is used for the input parameters and the Takagi-Sugeno linear model is used to construct the output membership function. Several rules based on the parameter change for different types of fault are framed using expert knowledge. Figure 20 shows the fuzzy based fault diagnosis system with five system parameters as inputs and five different conditions as outputs. The rules framed for the occurrences of faults in fuzzy inference system are as follows:

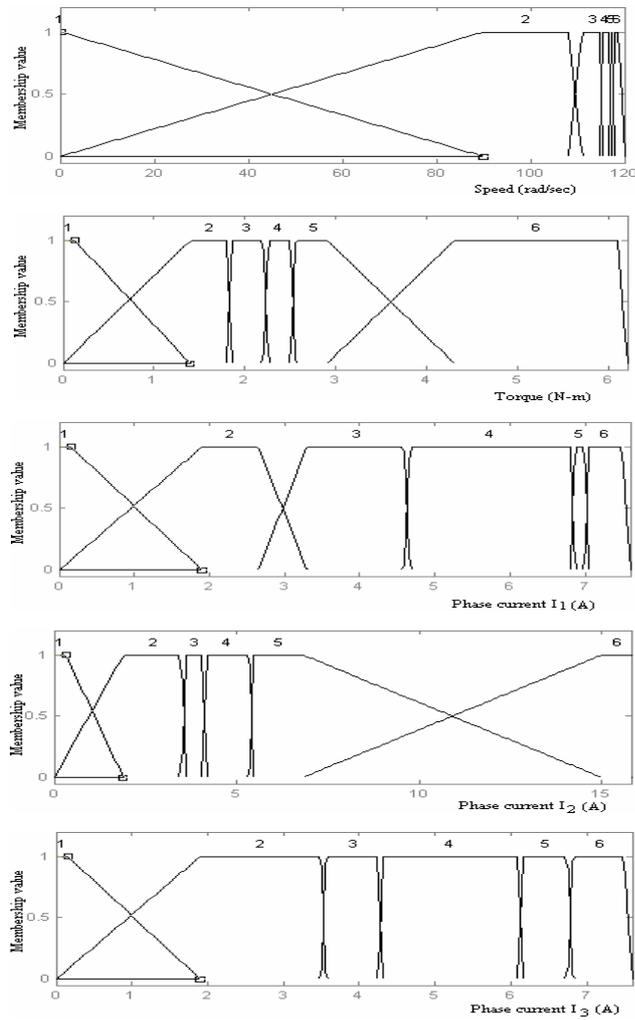


FIGURE 19. Membership functions of inputs to the fuzzy system

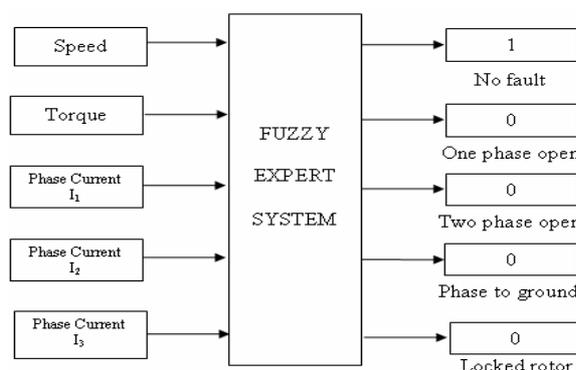


FIGURE 20. Fuzzy fault diagnosis system

- If speed is high, torque is medium and phase currents  $I_1$ ,  $I_2$  and  $I_3$  are normal, then there is 'no fault'.
- If speed is medium, torque is high, phase current  $I_1$  is zero and  $I_2$ ,  $I_3$  are normal, then the fault is 'one phase open circuit fault'.
- If speed is low, torque is high, phase currents  $I_1$ ,  $I_2$  are zero but  $I_3$  is high, then the fault is 'two phase open circuit fault'.
- If speed is zero, torque is zero, phase current  $I_1$  is zero,  $I_2$  is very high and  $I_3$  is again zero, then the fault is a 'locked rotor fault'.

Similarly, 25 rules are framed for the above-specified faults. Table 3 represents the ranges of parameters for the occurrence of a fault

Parameters Fault conditions	Speed (rad/sec)	Torque (N- m)	Phase Current (Amps)		
			$I_1$	$I_2$	$I_3$
One phase open	115.6 – 117.4	1.45 – 2.81	0 – 4.6	0 – 5.4	0 – 6.75
Two phases open	100 – 105	1.4 – 2.9	0 – 6.8	0 – 6.8	0 – 7.5
Phase to ground	115.3 – 117.3	1.4 – 2.82	0 – 5.7	0 – 6.5	0 – 6.2
Locked rotor	0	0	0	15.7	0

Table 3. Range of parameters for Single fault

**4.3.3 Fault Representation.** The occurrence of the fault conditions are classified as follows:

1.  $\phi^1 = [10000]$  if the input parameters correspond to nominal operating conditions
2.  $\phi^2 = [01000]$  if the input parameters correspond to a one phase open circuit
3.  $\phi^3 = [00100]$  if the input parameters correspond to a two phase open circuit

4.  $\phi^4 = [00010]$  if the input parameters correspond to one phase to ground fault

5.  $\phi^5 = [00001]$  if the input parameters correspond to a locked rotor position

Thus for a specific set of input parameters, the faults are diagnosed using a fuzzy based diagnosis scheme.

## 5. Conclusion

This paper describes the fault diagnosis and control concepts for a SR motor drive system based on analytical and expert knowledge. A FLC is successfully designed and it gives relatively better performance like reduced oscillations of the control variable compared to the conventional PI controller. Also, a fuzzy based fault detection scheme is proposed, where the parameters speed, torque and phase currents are derived from the analytical model for both normal and abnormal conditions. Different faults are identified by the set of rules in fuzzy inference system based on the observed parameters and using expert knowledge. The results show that the fuzzy system is able to identify the faults accurately.

## Appendix [12]

No of Phases	3
No of Stator poles	6
No of Rotor poles	4
Rated Voltage	150V
Rated Current	15A
Maximum Torque	2.2 N-m
Maximum Power	2.7 Kw
Inertia constant	0.0013
Phase Resistance	1.3 ohm
Inductance -Aligned	60 mH
-Unaligned	8 mH
Friction coefficient	0.0183
Maximum Speed	200 rad/sec

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N. SELVAGANESAN\*, DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING, PONDICHERRY ENGINEERING COLLEGE, PONDICHERRY-605014, INDIA  
E-mail address: [n\\_selvag@rediffmail.com](mailto:n_selvag@rediffmail.com)

D. RAJA, DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING, PONDICHERRY ENGINEERING COLLEGE, PONDICHERRY-605014, INDIA

S. SRINIVASAN, DEPARTMENT OF INSTRUMENTATION ENGINEERING, MIT CAMPUS, ANNA UNIVERSITY, CHROMEPET, CHENNAI-600044, INDIA  
E-mail address: [srini@mitindia.edu](mailto:srini@mitindia.edu)

\* CORRESPONDING AUTHOR