Fault Tolerance of 12/8 Switched Reluctance Motor Using Fuzzy logic Controller

J.Kartigeyan[1] and M.Ramaswamy[2], *Member, IEEE*

Abstract— The nature of the magnetic independence of the phase windings in a switched reluctance motor (SRM) enable it to operate despite partial failures occurring in the motor-converter unit. However on the occurrence of the fault, the speed and torque variations in the motor invite problems and urge attention. Therefore fault-tolerant SRM drive systems become the order of the day and assuage to explore fresh applications. The paper develops an adaptive fuzzy logic controller (FLC) for be-hiving a fault-tolerant ability to the SRM drive used in automobile applications. It allows continuously adapting its properties to regulate the machine speed and torque in accordance with the requirements of the drive system even under fault conditions. The action of the fuzzy system operates to generate the current reference and the inference system creates the rule base relating the parameters to the type of the faults under consideration. The rules engage the specific changes in the system parameters to diagnose the faults and evaluate the performance through its post-fault characteristics of the SRM in terms of torque and speed ripples to show its fault-tolerant capabilities. The reasoning philosophy of the FLC serves to exploit the inbuilt corrective prodigy in the SRM for arriving at precise operating requirements. The attributes of the inherent fault-tolerant features attach a sense of reliability to the motor and incite a new dimension for its use in the vehicular world.

Index Terms—Mathematical modeling, Faults, Fuzzy controller, Fault-tolerance, Switched reluctance motor.

◆

1 INTRODUCTION

THE switched reluctance motor (SRM), due to its simple and robust construction, controlling flexibility and inherent fault tolerant capability appears to attract attention for use in industrial and technical appliances. The magnetic independence between the phases in the motor permits the machine to keep running under faults through the role of an appropriate power converter and related control strategies. The peculiar attributes enable the SRMs to offer a competitive solution for aircraft and automotive applications where systems reliability turns out to be of crucial significance.

Though the machine enjoys the feature to operate under faulted states, the electromagnetic and mechanical behavior continues to deteriorate and consequently the output power decreases proportionally with the number of lacking phases. Besides unbalanced forces attempt to be generated in the motor and pave the way for improper dynamic equilibrium in its functioning.

Despite the innate existence of a fault tolerant behavior, still the occurrence of a fault and its consequences demand exclusive corrective actions for the compliance of a satisfactory operation. A host of control schemes do exist to provide remedial measures and heal the impaired status. Among the innumerable approaches, the intelligent controllers find a place to resurrect the fault and ensure a greater range of reliability to the motor.

In recent years, various studies on fault-tolerant control methods and fault-tolerant SRM constructions have been carried on to enhance the operation performance of the machine [1]-[16].

The electrical faults such as short and open circuits in SRM drive have been systematically classified and the fault patterns and possible remedial solutions investigated in [1] and [2]. The non-operation of the motor phases have been caused either by electrical faults in the motor itself or in the power converter. Many fault tolerant power converters in a perspective to address the faults in the SRM have been investigated in [2]-[6].

Under power switch open-circuit fault conditions, different electrical connections have been thought of to recreate the path for the conduction of additional power switches. Many fault diagnostic and fault-tolerant control strategies have been put in place in [7]-[13] to reduce the transient time between the faults and restore the normal operation. These methods have been able to identify the fault accurately and augur the needs of the fast changes in the control strategy and or the power converter topology.

Owing to the development of fault-tolerant control schemes and power converter topologies, some new SRM constructions such as modular stator [14], segment stator SRMs [15], higher number rotor poles SRM [16], new rotor structure SRM [17] and double-layer-per-phase isolated SRM [18] have been suggested with improved fault-tolerant capability.

In spite of the developments there exists a requirement to expand the scope of the controllers and bring in better erudite mechanisms for fostering the reliable operation of the SRM. The primary emphasis owes to design a fuzzy based controller, capable of delivering almost constant speed and torque for the SRM even under fault conditions. The adaptive algorithm orients to provide the precise

---

J. Kartigeyan is with the department of Electrical Engineering, Annamalai University, Chidambaram, Tamilnadu-608 002, India. Phone: +91 9489562011; (e-mail: j.kartigeyan@gmail.com)

M.Ramaswamy is with the department of Electrical Engineering, Annamalai University, Chidambaram, Tamilnadu-608 002, India. Phone: +919042915160; (e-mail: prof.m.ramaswamy@gmail.com)

current reference for generating the switching pulses in order that it forges the power converter to attenuate the fault in the SRM in addition to minimizing the torque ripple. The methodology extends to examine the performance of the motor using its post fault characteristics and establish the suitability of the FLC for use with the SRM.

2 MATHEMATICAL MODEL OF SR MOTOR

The instantaneous voltage of a SR motor across the terminals of a phase winding is related by Faraday's law in Eq. 1

$$V = RI + \frac{\partial \phi}{\partial I}\frac{dI}{dt} + \frac{\partial \phi}{\partial \theta}\frac{d\theta}{dt} \qquad (1)$$

Where, *V*- Terminal voltage, *I*- Phase current, *R*- Phase winding resistance and ϕ -Flux linked by the windings. The phase inductance displaced by an angle θ_s in the profile seen in Fig. 1 is expressed using Eq.2

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

Where N_s and N_r are the number of rotor and stator poles.

The flux in each phase is given by Eq. 3

$$d\phi_i(\theta, I_i) = L(\theta)\cdot I_i \qquad (3)$$

Where *i* is the phase (*i* =1, 2 and 3)

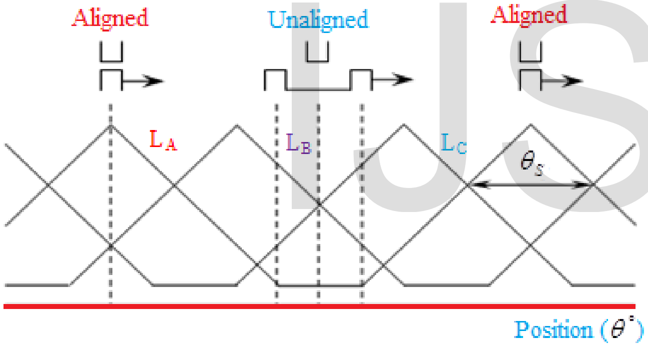


Fig.1. Inductance profile of the SR motor drive

The total energy associated with the three phases is governed by Eq.4

$$W_{tot} = \frac{1}{2}\sum_{i=1}^{3} L(\theta + (n - i - 1)\theta_s)\, I_i^2 \qquad (4)$$

The total torque developed by the motor is given by Eq.5

$$T = \frac{1}{2}\sum_{i=1}^{3} \frac{dl(\theta + (n - i - 1)\theta_s)}{d\theta} I_i^2 \qquad (5)$$

The mechanical equations are related through Eq.6

$$J\frac{d\omega}{dt} = T - T_L - f\omega \text{ and } \frac{d\theta}{dt} = \omega \qquad (6)$$

Where, *J*-Moment of inertia, T_L-Load torque, f-Friction coefficient.

3 FAULTS IN SR MOTOR

The SRM inherits a number of advantages over other electric motors such as structural simplicity, high reliability and low cost. However the motors require operating under various environmental conditions and become prone to experiencing fault conditions. The various faults that occur in SRMs include

1. One Phase Open Circuit Fault
2. Two Phase Open Circuit Fault
3. Phase to Ground Fault
4. Short circuit Fault
5. Locked Rotor Fault
6. One Phase Open Circuit and Phase to Ground Fault

1. One Phase Open Circuit Fault

It occurs when any one of the phases of the SRM become open and results in zero current in the corresponding phase. Consequently it may not contribute to torque production from that phase.

2. Two Phase Open Circuit Fault

It results when two of the phases of the SRM open and prevents the flow of current in the two phases on account of which there ceases to be any torque production from those phases.

3. Phase to Ground Fault

It emanates when any one of the phase winding of the SRM becomes short circuited to the grounded components such as the stator core to end up with over current in that phase.

4. Short circuit Fault

It arises when any one of the phase winding of the SRM remains short circuited to create an over current in the corresponding phase.

5. Locked Rotor

The rotor becomes obstructed and prevented from rotation due to a possible mechanical reason and engages a locked rotor condition. It can be tolerated only for a limited time and necessitates to be switched off immediately.

6. One Phase Open Circuit and Phase to Ground Fault

It occurs when one of the phase winding of the SRM short circuits to the grounded components such as the stator core and the other phase is open circuited to end up in over current in that phase.

4. DESIGN OF FUZZY LOGIC CONTROLLER

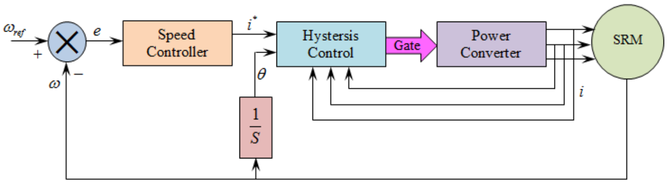


Fig.2. Block diagram of the SR motor drive

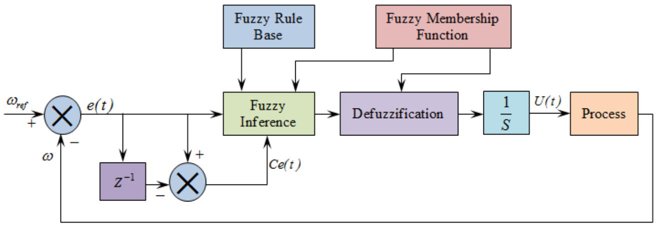


Fig.3. Block diagram of the FLC system

The exercise relates to the choice of a 3 phase - 12/8 switched reluctance motor together with a 2- switch per phase bridge converter topology. The FLC explained using the block diagram in Fig. 2 involves 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 and includes a hystersis control for regulating the current in the designated phase.

The design of the FLC in Fig.3 depends on the input variables 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 related using Eq. 7,

$$u(t) = u(t-1) - \Delta u(t) \tag{7}$$

4.1 Procedure

The basic procedure for implementing the fuzzy logic controller involves 4 steps,

1. Forming the table manually
2. Creating the Fuzzy Controller in MATLAB
3. Checking the Fuzzy controller
4. Using it in Simulink.

The two inputs considered are e (k) and Δe (k) and operates on the basis of Eq.8 through Eq.11.

$$e(k) = \omega_{ref} - \omega(k) \tag{8}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{9}$$

$$\Delta e(k) = [\omega_{ref} - \omega(k)]-[\omega_{ref} - \omega(k-1)] \tag{10}$$

$$\Delta e(k) = \omega(k-1) - \omega(k) \tag{11}$$

4.2 Cases

1. $e(k) < 0$ and $\Delta e(k) < 0$

It means that $\omega(k) > \omega_{ref}$ and $\omega(k) > \omega(k-1)$, meaning ω is rising and moving away from ω_{ref}. and requires a negative control action.

2. $e(k) > 0$ and $\Delta e(k) > 0$

It implies that $\omega(k) < \omega_{ref}$ and $\omega(k) < \omega(k-1)$, meaning ω is decreasing and moving away from ω_{ref} and necessitates a positive control action.

3. $e(k) > 0$ and $\Delta e(k) < 0$

It indicates that $\omega(k) < \omega_{ref}$ and $\omega(k) > \omega(k-1)$, meaning ω is increasing and moving towards ω_{ref} .

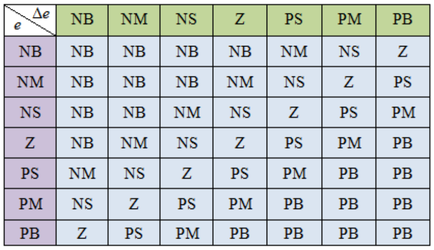
4. $e(k) < 0$ and $\Delta e(k) > 0$

It signifies that $\omega(k) > \omega_{ref}$ and $\omega(k) < \omega(k-1)$, meaning ω is decreasing and moving towards ω_{ref}.

5. $e(k) = 0$ and $\Delta e(k) = 0$

It shows that $\omega(k) = \omega_{ref}$ and $\omega(k) = \omega(k-1)$, meaning $\omega = \omega_{ref}$ for at least two instants of control action. So the control action is suspended.

Table 1. Rule database



e \ Δe	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

The 7 X 7 Membership function (input/output) shown in Table 1 behoves the rules used for controlling the error to maintain speed at desired set point. The triangular with Z and S membership functions in Fig.4 also includes the symmetrical *S* and *Z* functions for NB and PB respectively. The choice of *Z* and *S* membership functions instead of triangular membership functions favor the smooth transition during the transient period.

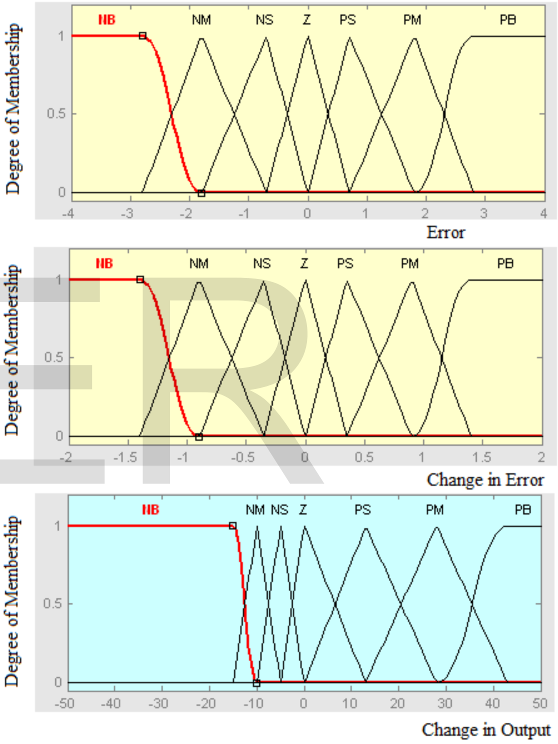


Fig.4. Membership functions

5 SIMULATION

The procedure attempts to evaluate the performance of the 12/8 SRM drive with the parameters that read three phase, 1.5 Kw, 72 V, 5100 r.p.m, 2.8 N-m, J = 0.0013 and B = 0.0183 on the MATLAB platform.

5.1 One Phase and Two phase Open Circuit Fault

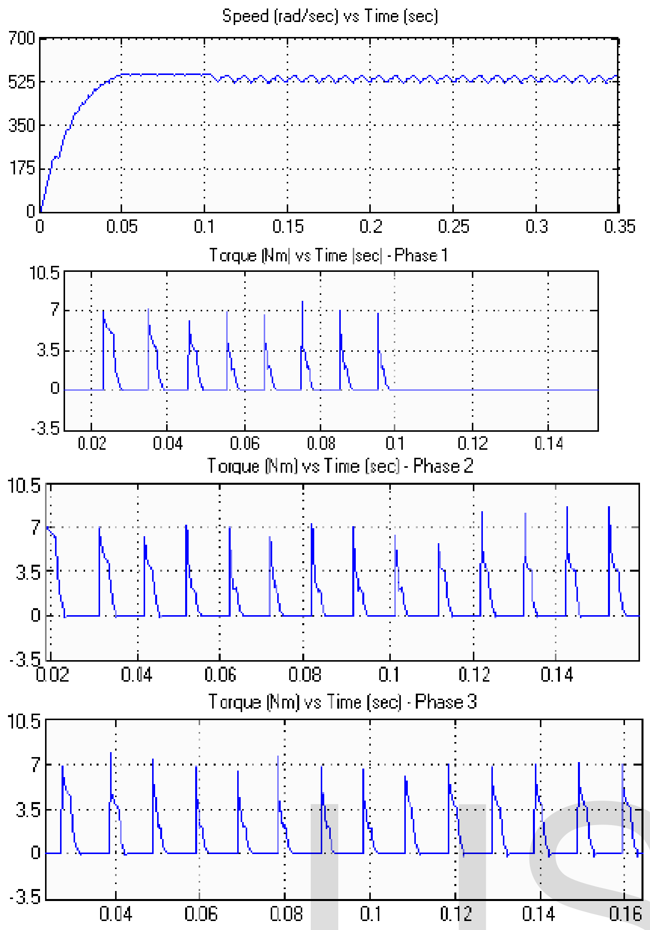
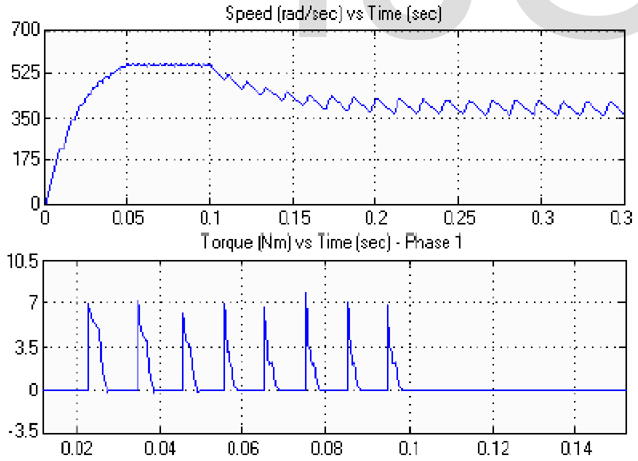


Fig.5. One phase open circuit fault



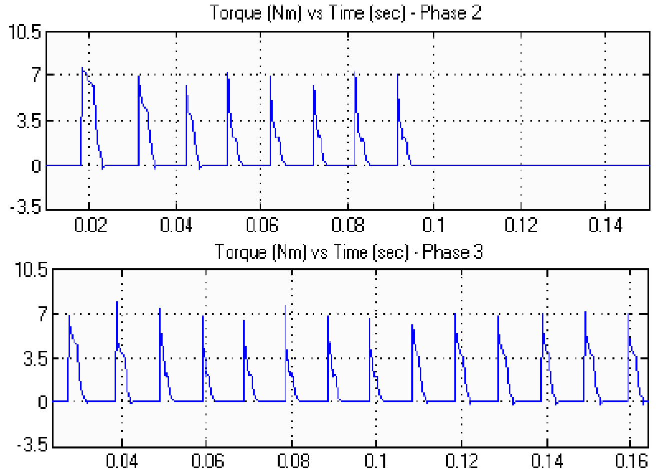
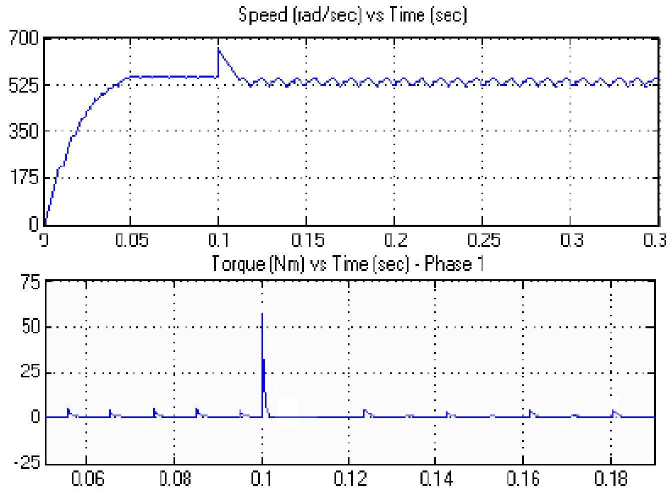


Fig.6. Two phase open circuit fault

The Fig.5 displays the speed and torque responses for the one phase open circuit fault introduced at 0.1 Second. The speed and torque curves in responses in Fig.6 for the two phase open circuit fault created by opening of two phases at the same 0.1 second.

5.2 Phase to Ground and Short circuit Fault, and Over Load Behavior

The Fig. 7 explains the variations of the speed and torque curves for an increase in the phase current at particular instant of 0.1 Second. The Fig.8 depicts the speed and torque responses when a short circuit fault enters by applying overload at 0.1 second. The process continues to illustrate the overload behaviour of the SRM by applying almost 400% to 500% of normal operating torque for a limited time through the corresponding speed and torque responses shown in Fig.9.



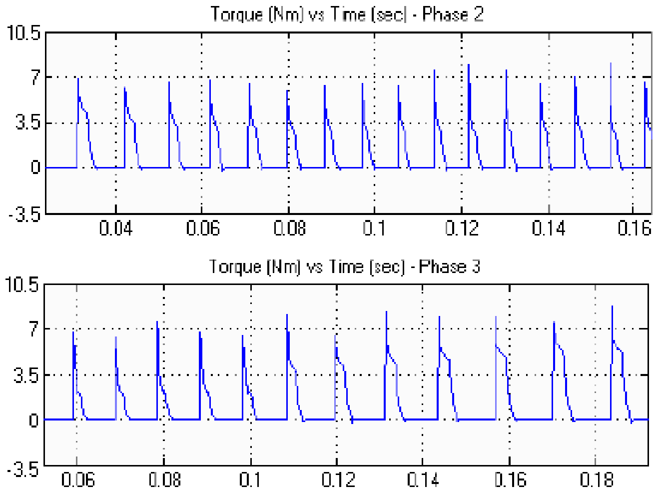


Fig.7. Phase to Ground Fault

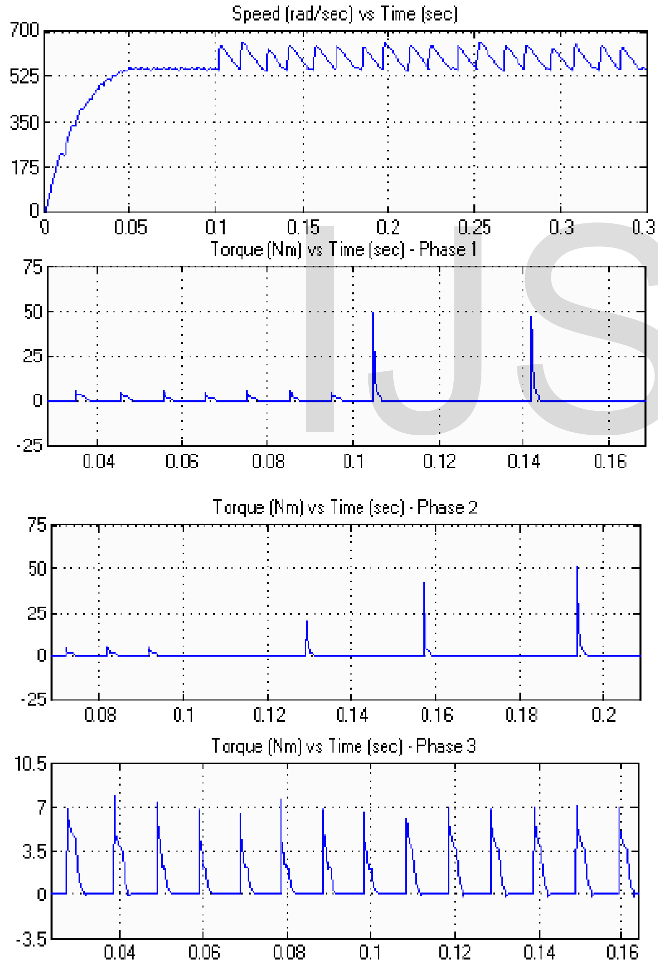


Fig.8. Short circuit Fault

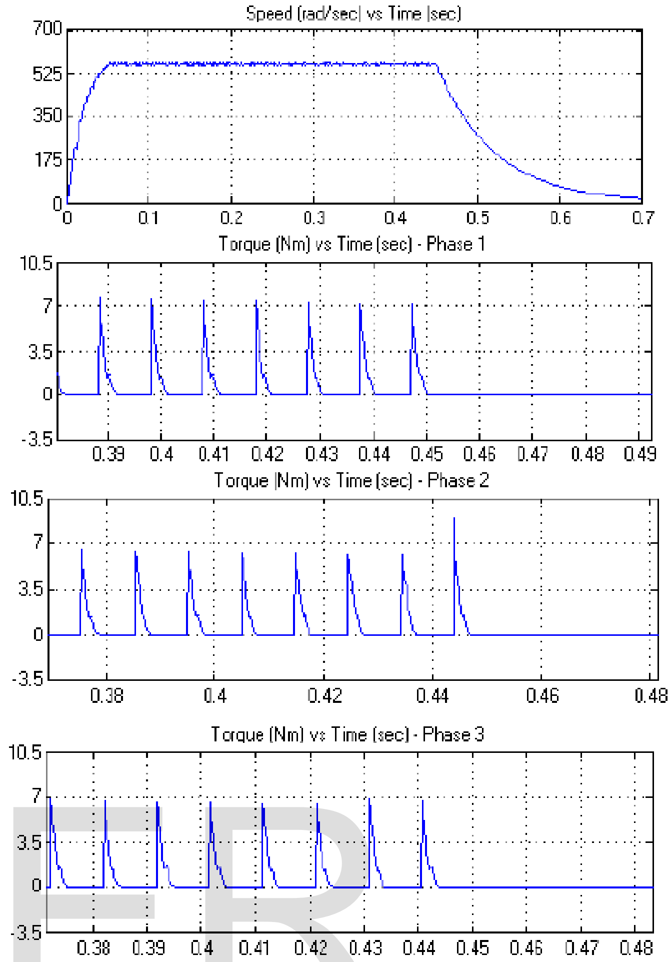


Fig.9. Locked Rotor

6 CONCLUSION

A FLC has been designed to incorporate the fault tolerant capability for the SRM through the use of the design equations of the motor. The study has been carried out with different fault conditions for the SRM model at the chosen instant of time. The simulated speed and torque responses have been portrayed for enumerating the ability of the FLC in enabling the SRM to reject the fault and operate in the stable state. The set of rules in the fuzzy inference system obtained based on expert knowledge have been the guiding force in building the fault tolerance to the SRM. The results have been projected to establish the benefits of the FLC and allow the SRM to cater the needs of the automobile industry with a higher sense of reliability.

REFERENCES

[1] S. Gopalakrishnan, A.M. Omekanda and B. Lequensne, “Classification and remediation of electrical faults in the switched reluctance drive,” *IEEE Trans. Ind. Appl.*, vol. 42, no. 2, pp. 479–486, Mar. 2006.

[2] B. Lequesne, S. Gopalakrishnan and A.M. Omekanda, “Winding short circuits in the switched reluctance drive,” *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1178–1184, Sep. 2005.

[3] K. Lee, N. Park, K. Kim, and D. Hyun, “Simple fault detection and tolerant scheme in VSI-fed switched reluctance motor,” in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 18–22, 2006, pp. 1–6.

[4] C. Oliveira, A. M. N. Lima, C. B. Jacobina, and F. Salvadori, “Startup and fault tolerance of the SRM drive with three-phase bridge inverter,” in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2005, pp. 714–719.

[5] N. S. Gameiro and A. J. M. Cardoso, “Fault tolerant power converter for switched reluctance drives,” in *Proc. Int. Conf. Elect. Mach.*, Sep. 6–9,2008, pp. 1–6.

[6] M.D. Hennen, M. Niessen, C. Heyers, H.J. Brauer and R.W De Doncker, “Development and control of an integrated and distributed inverter for fault tolerant five-phase switched reluctance traction drive,” *IEEE Trans. Power Eletron.*, vol. 27, no. 2, pp. 547–554, Feb. 2012.

[7] N. S Gameiro and A.J.M. Cardoso, “Power converter fault diagnosis in SRM drives based on DC-bus current analysis,” in *Proc. International conference on Electrical Machines*, Sept. 2010, pp. 1–6.

[8] L.A. Belfore and A. Arkadan, “A methodology for characterizing fault tolerant switched reluctance motors using neurogenetically derived models,” *IEEE Trans. Energy Convers*., vol. 17, no. 3, pp. 380–384, Sep. 2002.

[9] S. Mir, M.S. Islam, T. Sebastian and I. Husain, “Fault-tolerant switched reluctance motor drive using adaptive fuzzy logic controller,” *IEEE Trans. Power Eletron*., vol. 19, no. 2, pp. 289–295, Mar. 2004.

[10] H. Chen and S. Lu, “Fault diagnosis digital method for power transistors in power converters of switched reluctance motors,” *IEEE Trans. Ind. Eletron*., vol. 60, no. 2, pp. 749–763, Feb. 2013.

[11] N.S. Gameriro and A.J. Marques Cardoso, “A new method for power converter fault diagnosis in SRM drives,” *IEEE Trans. Ind. Appl.*, vol. 48, no. 2, pp. 653–662, Nov. 2012.

[12] H. Torkaman and E. Afjei, “Sensorless method for eccentricity fault monitoring and diagnosis in switched reluctance machines based on stator voltage signature,” *IEEE Trans. Magn*. vol. 49, no. 2, pp. 912–920, Feb. 2013.

[13] H. Torkaman, E. Afjei and P. Yadegari, “Static, dynamic, and maxed eccentricity faults diagnosis in switched reluctance motor using transient finite element method and experiments*”, IEEE Trans. Magn*. vol. 48, no. 8, pp. 2254–2264, Aug. 2012.

[14] M. Ruba, I.A. Viorel and L. Szabo, “Modular stator switched reluctance motor for fault tolerant drive systems,” IET Electric Power Application, vol. 7, no. 3, pp. 1098–1102, Mar. 2013.

[15] L. Szabo and M. Ruba, “Segmental stator switched reluctance machine for safety-critical applications,” *IEEE Trans. Ind. Appl.*, vol. 48, no. 6, pp. 2223–2229, Nov. 2012.

[16] B. Bilgin, A.Emadi and M. Krishnamurthy, “Design consideration for switched reluctance machines with a higher number of rotor poles,” *IEEE Trans. Ind. Eletron*., vol. 59, no. 10, pp. 3745–3756, Oct. 2012.

[17] L. Gu, W. Wang, B. Fahimi, A. Clark and J. Hearron, “Magnetic design of two-phase switched reluctance motor with bidirectional startup capability,” *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2148 - 2155, Jun. 2016.

[18] H. Torkaman, E. Afjei and M. S. Toulabi, “New double-layer-per-phase isolated switched reluctance motor: concept, numerical analysis, and experimental confirmation,” IEEE Trans. Ind. Eletron., vol. 59, no. 2, pp. 830 - 838, Feb. 2012.