DOI: 10.21917/ijsc.2011.0035

FUZZY FAULT DETECTION FOR PERMANENT MAGNET SYNCHRONOUS GENERATOR

N. Selvaganesan[1] and R. Saraswathy Ramya[2]
[1]*Department of Avionics, Indian Institute of Space Science and Technology, Kerala, India*
E-mail: n_selvag@rediffmail.com
[2]*SAP Labs India Private Limited, Bangalore, India*
E-mail: saraswathy.ramya@sap.com

Abstract
Faults in engineering systems are difficult to avoid and may result in serious consequences. Effective fault detection and diagnosis can improve system reliability and avoid expensive maintenance. In this paper fuzzy system based fault detection scheme for permanent magnet synchronous generator is proposed. The sequence current components like positive and negative sequence currents are used as fault indicators and given as inputs to fuzzy fault detector. Also, the fuzzy inference system is created and rule base is evaluated, relating the sequence current component to the type of faults. These rules are fired for specific changes in sequence current component and the faults are detected. The feasibility of the proposed scheme for permanent magnet synchronous generator is demonstrated for different types of fault under various operating conditions using MATLAB/Simulink.

Keywords:
Fuzzy Fault Detector, Membership Function, Sequence Component

1. INTRODUCTION

Permanent Magnet Synchronous Generators (PMSGs) are receiving significant attention from industries for the last two decades. They have numerous advantages over the machines which are conventionally used. Current research in the design of the PMSG indicates that it has high torque to current ratio, large power to weight ratio, high efficiency, high power factor and robustness [1]. Currently, there is much interest in using brushless electronically commutated servo machines in high performance electromechanical systems and the application of neodymium-iron-boron ($Nd_2Fe_{14}B$) and samarium cobalt (Sm_1Co_5 and Sm_2Co_{17}) rare-earth magnets resulting in high torque and power density, efficiency and controllability, versatility and flexibility, simplicity and ruggedness, reliability and cost, weight-to-torque and weight-to-power ratios, better starting capabilities [2]-[5].

Fault detection and diagnosis is important in engineering systems to avoid serious consequences. In complex systems, any fault possesses the potential to impact the entire system's behavior. In a manufacturing process, a simple fault may result in off specification products, higher operation costs, shutdown of production lines, and environmental damage, etc. In a continuously operated system, ignoring a small fault can lead to disastrous consequences.

A number of approaches have been proposed in recent years for the detection and diagnosis of failures in dynamic systems which provides online monitoring of electrical machines [6]-[7]. 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 and reliability standards [8].

Modeling of synchronous machines with shorted turns is the first step in the design of turn fault detection systems [9]-[10]. Models exhibit complex relationship between parameters and exact fault signature extraction is very difficult. The utility of machine model is restricted because it is even theoretically impossible to include all no idealities of the machine. The environmental factors such as temperature of machine and operational factors like speed and excitation current can affect the fault signature [11]. The fault detection based on the monitoring of spectrum vibration has been reported in [12]. The accurate sensing devices are required to monitor the vibration spectrum for fault signature and they are expensive.

The negative sequence components of voltage and current are used to detect the inter-turn fault and is obtained from the line voltages and currents which is given as inputs to Fuzzy Fault Detector (FFD) is discussed in [13]. The different methods of fault diagnosis are discussed in [14]-[15]. The fuzzy based fault detection and diagnosis scheme for switched reluctance motor is presented in [16]. The fault detection scheme for permanent magnet synchronous motor drive by considering electrical faults such as stator resistance and q- axis inductance as uncertainties has been reported in [17].

This paper deals with fuzzy based fault detection of PMSG. A fuzzy logic system is created for fault diagnosis purposes. Whenever there is a fault in the system, it will introduce unbalance in line currents. The winding unbalance injects unbalance in positive sequence and negative sequence current in machine which is used as fault indicators. Subsequently the fault is detected by means of fuzzy inference system. Various possible faults are simulated and detected using fuzzy fault detector in MATLAB/Simulink environment.

The rest of the paper is organized as follows. The open loop PMSG modeling and its simulation is dealt in Section 2. Simulation results under fault condition are discussed in Section 3. In Section 4 the fault detection concept and its simulation using fuzzy fault detection is explained. Conclusion is narrated with Section 5.

2. THE PMSG SYSTEM MODEL

The dynamic characteristics of a PMSG can be modeled based on the d-q axis and the differential equations that describe the circuitry and torsional-mechanical dynamics is given in [1]-[5]. The transient dynamics of generator must be integrated with prime mover equations. Consider the generation system when the permanent magnet DC motor is used as prime mover, whose differential equations are as follows,

$$\frac{di_a}{dt} = \frac{r_a}{L_a} i_a - \frac{k_a}{L_a}\omega_r + \frac{1}{L_a} u_a \tag{1}$$

$$\frac{d\omega_{rm}}{dt} = \frac{k_a}{J} i_a - \frac{3P\psi_m}{4J} i^r_{qs} - \frac{B_m}{J}\omega_{rm} \tag{2}$$

$$\frac{d\theta_{rm}}{dt} = \omega_{rm} \tag{3}$$

where, r_a, L_a, i_a, k_a are armature resistance, armature inductance, armature current, armature constant respectively. ω_r, ω_{rm} and θ_{rm} are angular velocity, mechanical angular velocity and mechanical angular displacement respectively. P is number of poles. Ψ_m is flux linkages. B_m and J are moment of inertia and viscous friction co-efficient respectively. In the rotor reference frame, the mathematical model of three phase PMSG [1] with resistive load can be expressed as follows,

$$\frac{di^r_{qs}}{dt} = -\frac{r_s + R_L}{L_{ls} + \frac{3}{2}\bar{L}_m} i^r_{qs} + \frac{\psi_m}{L_{ls} + \frac{3}{2}\bar{L}_m}\frac{P}{2}\omega_{rm} - \frac{P}{2} i^r_{ds}\omega_{rm} \tag{4}$$

where i^r_{qs}, i^r_{ds} are are q-axis current and d-axis current component respectively. R_L and r_s are load resistance and stator resistance respectively. L_{ls} and $\bar{L}_m$ are leakage and magnetizing inductance respectively. The q-axis voltage and d-axis voltage are given [1] as follows,

$$u^r_{ds} = -\left(r_s + \frac{d}{dt}L_{ds}\right)i^r_{ds} + \omega_r L_{qs} i^r_{qs} \tag{6}$$

$$u^r_{qs} = -\left(r_s + \frac{d}{dt}L_{qs}\right)i^r_{qs} - \omega_r L_{ds} i^r_{ds} + \omega_r \psi_m \tag{7}$$

where u^r_{qs}, u^r_{ds} are q- axis stator voltage component and d-axis stator voltage component respectively. L_{qs} and L_{ds} denotes q-axis and d-axis inductance respectively. $L_{ls} + \frac{3}{2}\bar{L}_m$ is L_{ss}, which is the self inductance of stator winding. By means of Park's transformation the 2-axis quantity is converted into 3-axis quantity and the rated three phase current and voltages are generated. The open loop system is simulated with specification given in Appendix I. Fig.1 to Fig.4 shows the three phase voltage, three phase current, positive sequence current and negative sequence current under normal operating condition when the load is maintained at 50 Ω.

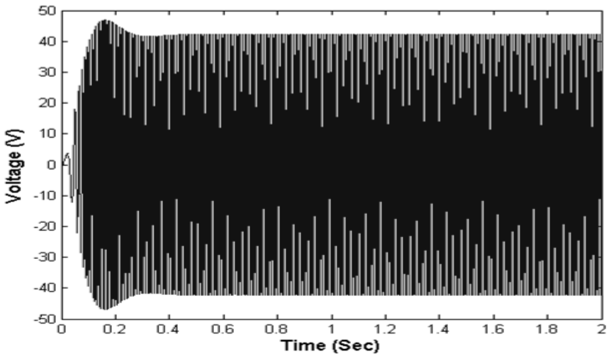

Fig.1. Three phase voltage under normal operating condition

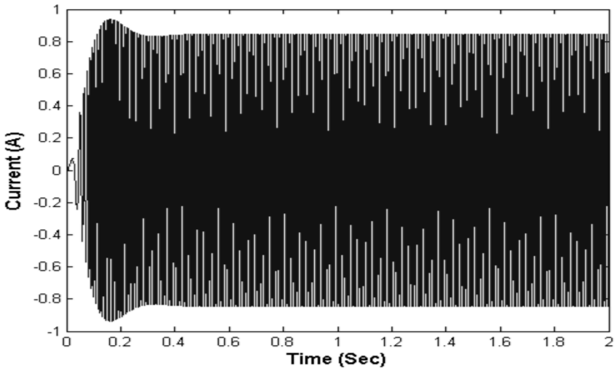

Fig.2. Three phase current under normal operating condition

$\frac{di^r_{ds}}{dt}$

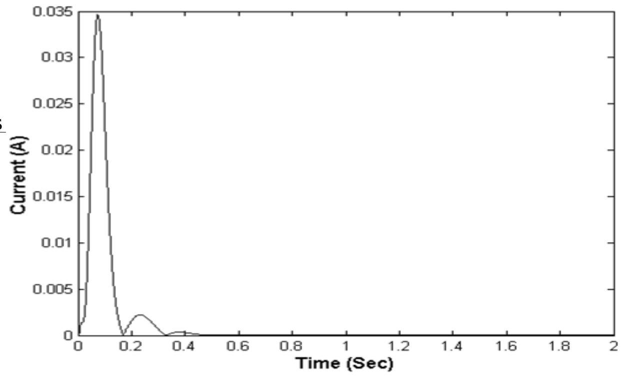

Fig.3. Positive sequence current under normal operating condition

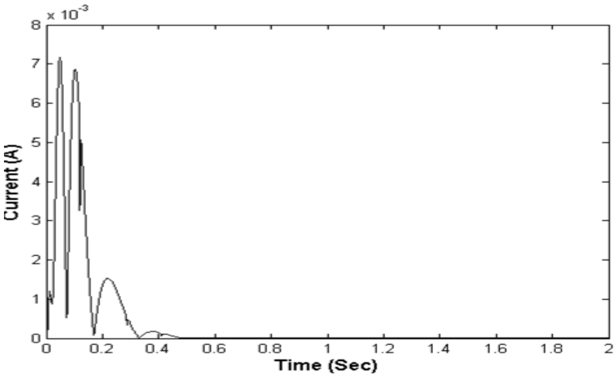

Fig.4. Negative sequence current under normal operating condition

3. FAULTS SIMULATION

The faults that usually occur in PMSG are rotor fault, overload, mechanical fault, Line to Ground Fault (L-G), Double Line to Ground fault (L-L-G) and combination of over load-rotor fault. The simulations are carried out under different operating conditions.

3.1 ROTOR FAULT (FLUX DISTURBANCE)

For induction machines, the rotor fault mainly indicates broken bars, whereas for permanent magnet machines, it means magnet defects. This fault can be the results of pulsating load, or certain manufacturing problems. Rotor faults will cause speed fluctuations, vibrations, abnormal noises, etc. The rotor fault is introduced by varying flux (ψ) to 25% and 50% of rated value during normal simulation. The Fig.5 to Fig.7 represent responses of three phase current, positive sequence current and negative sequence current for ψ varied from 0.054 N-m-A^{-1} to 0.027 N-m-A^{-1} at 1 sec under a constant load of 50Ω.

3.2 OVER LOAD (OVER HEATING)

The over loading of generator will results in overheating. It can also due to over current operation. The maximum permitted temperature for ordinary generator is about 40°C. Extreme high temperature operation is very detrimental to generator performance. The over load is introduced by varying load (R_L) from 120% to 150% under normal operating condition. The Fig.8 to Fig.10 represent responses of three phase current, positive sequence current and negative sequence current for variation in R_L from 50Ω to 4.794 Ω at 1sec.

3.3 MECHANICAL FAULT

Mechanical fault is mainly due to the unanticipated variation of moment of inertia (B_m) and viscous friction co-efficient (J) which may be caused due to bearing faults, lack of lubrication, over loading and air gap eccentricity. This fault usually generates excessive vibrations which causes incorrect generator operation and leads to extra maintenance downtime and cost etc. The mechanical fault is introduced by varying B_m and J from 125% to 150% of rated value. The Fig.11 to Fig.13 represent responses of three phase current, positive sequence current and negative sequence current for variation in B_m and J at 1sec under constant load of 50 Ω.

3.4 ELECTRICAL FAULT

The electrical fault is mainly due to abnormal variation of R_s and L_q which will leads to extreme heating in the generator windings. This will reduce the efficiency of generator and sometimes damages the machine itself. Fig.14 to Fig.16 shows the three phase current, positive sequence current and negative sequence current under electrical fault i.e variation of R_s and L_q at 1sec under constant load 50 Ω.

3.5 LINE TO GROUND FAULT

This situation occurs when any one of the phase of PMSG is shorted to ground. During L-G, the short circuit current rises, the voltage at the generator terminal drops. Due to dip in voltage, output power and electromagnetic torque are reduced significantly. Fig.17 to Fig.19 shows the three phase current, positive sequence current and negative sequence current under L-G fault at 1sec under constant load 50 Ω.

3.6 DOUBLE LINE TO GROUND FAULT

This condition occurs when any two phases of PMSG is shorted to ground. Similar to L-G fault, the short circuit current raises enormously, the voltage at the generator terminal drops. Fig.20 to Fig.22 shows the three phase current, positive sequence current and negative sequence current under L-L-G fault at 1sec under constant load 50Ω.

3.7 TWO FAULT (COMBINATION OF OVER LOAD AND ROTOR FAULT)

The overloading of the system, may influence on the rotor bar, resulting in breaking or cracking of bar. This will leads to the decrease in flux (ψ) there by affecting the overall performance of the machine. The over load-rotor fault is introduced at the rated load of 10 Ω. The Fig.23 to Fig.25 shows the responses of three phase current, positive sequence current and negative sequence current when rotor fault and overload occur simultaneously at 1sec.

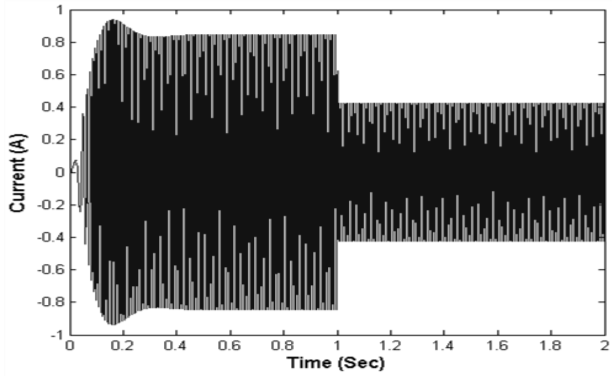

Fig.5. Three phase current under rotor fault at 1 sec

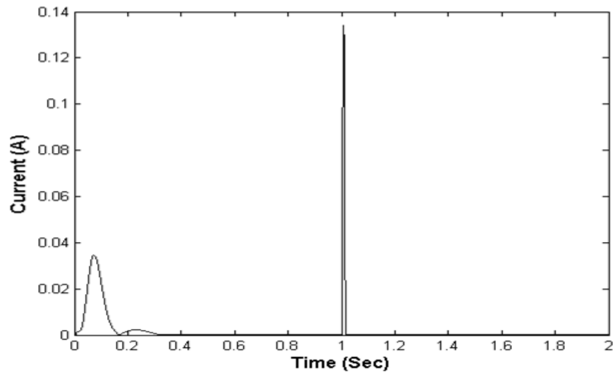

Fig.6. Positive sequence current under rotor fault at 1 sec

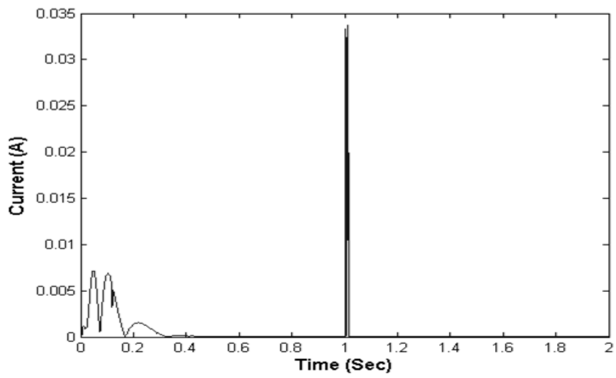

Fig.7. Negative sequence current under rotor fault at 1 sec

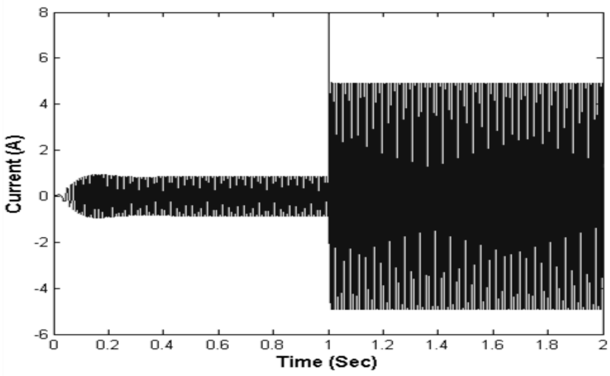

Fig.8. Three phase current under over load at 1 sec

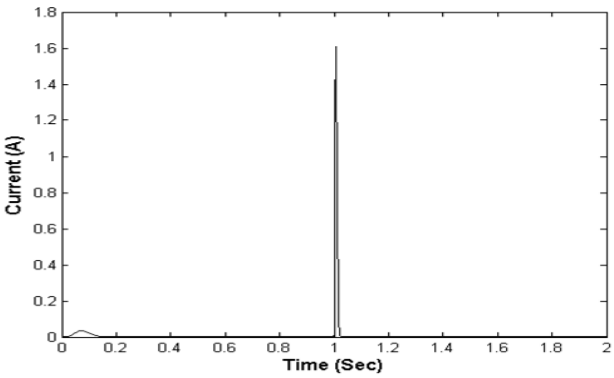

Fig.9. Positive sequence current under over load at 1 sec

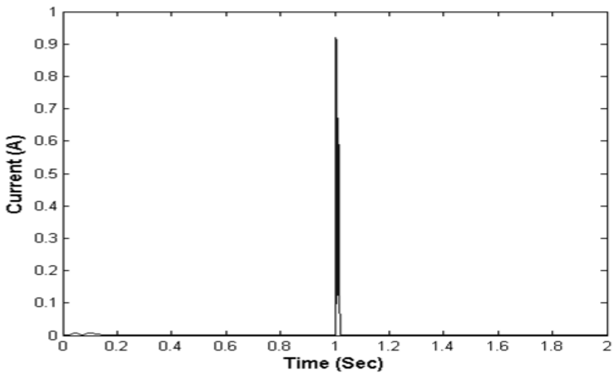

Fig.10. Negative sequence current under overload at 1 sec

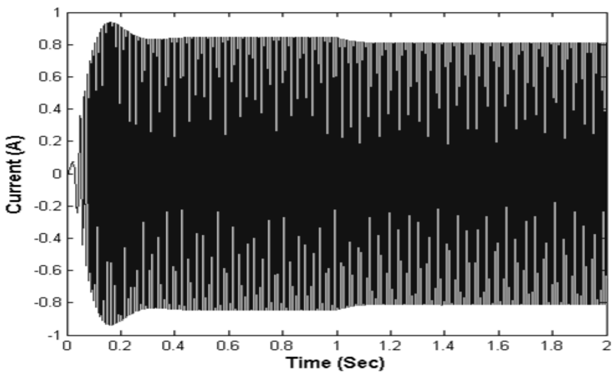

Fig.11. Three phase current under mechanical fault at 1 sec

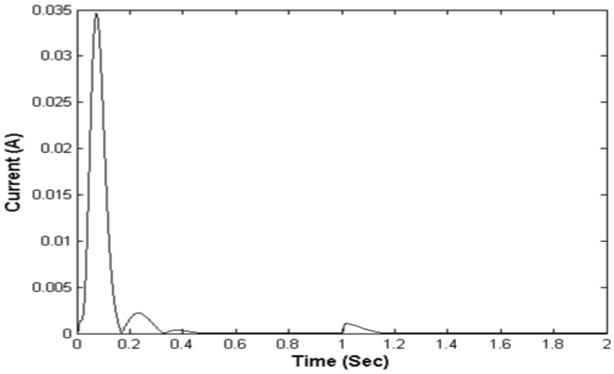

Fig.12. Positive sequence current under mechanical fault at 1sec

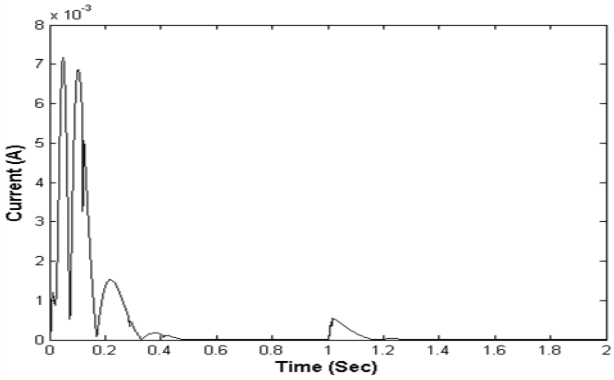

Fig.13. Negative sequence current under mechanical fault at 1sec

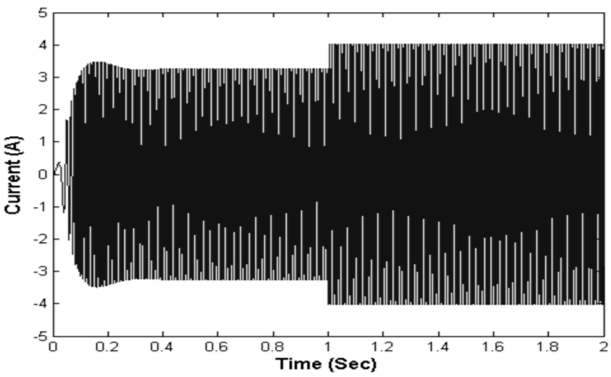

Fig.14. Three Phase current under electrical fault variation of R_s and L_q at 1sec

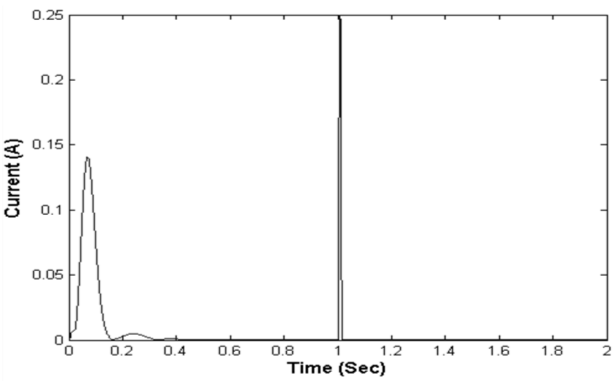

Fig.15. Positive sequence current under electrical fault variation of R_s and L_q at 1sec

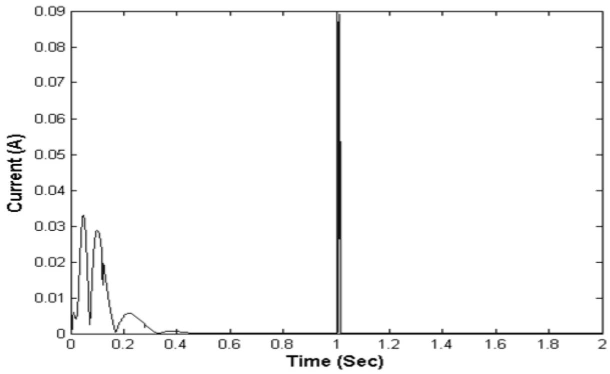

Fig.16. Negative sequence current under electrical fault variation of R_s and L_q at 1sec

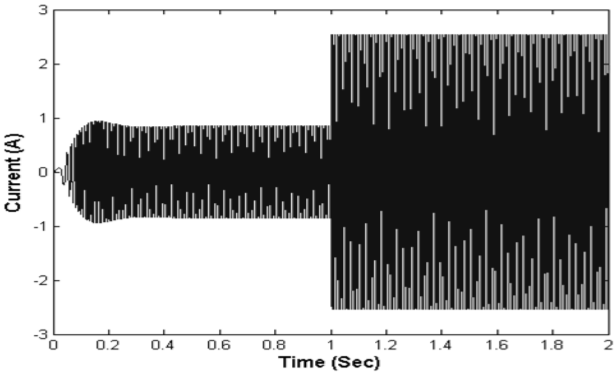

Fig.17. Three Phase current under L-G fault at 1sec

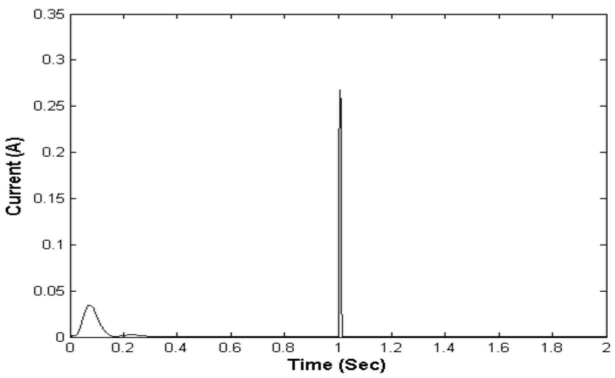

Fig.18. Positive sequence current under L-G fault at 1sec

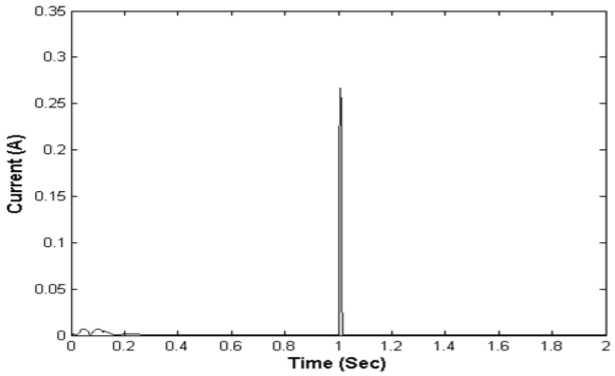

Fig.19. Negative sequence current under L-G fault at 1sec

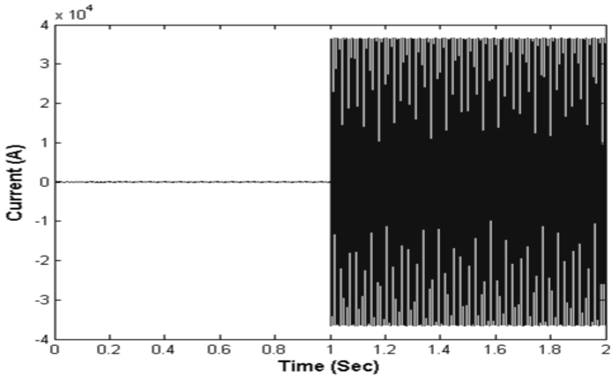

Fig.20. Three Phase current under L-L-G fault at 1sec

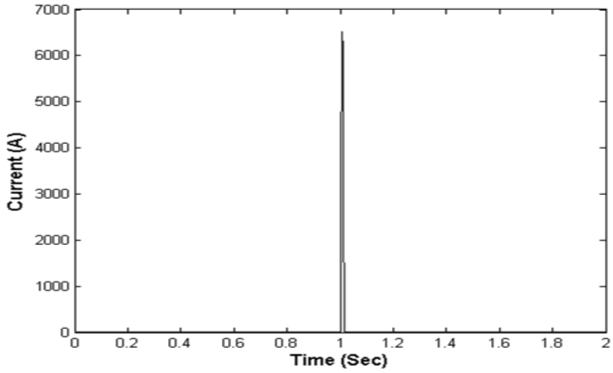

Fig.21. Positive sequence current under L-L-G fault at 1sec

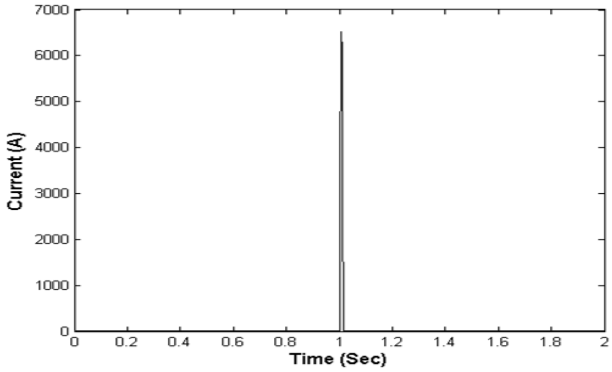

Fig.22. Negative sequence current under L-L-G fault at 1sec

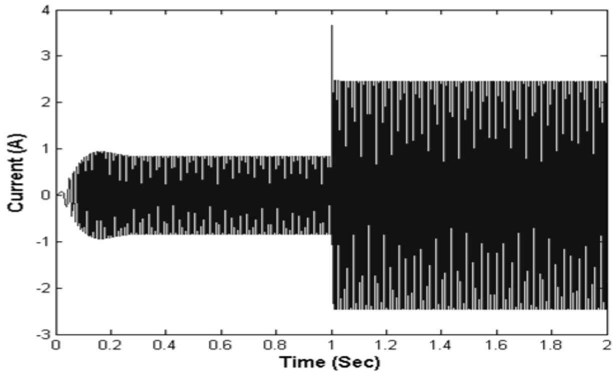

Fig.23. Three phase current under over load and rotor fault at 1sec

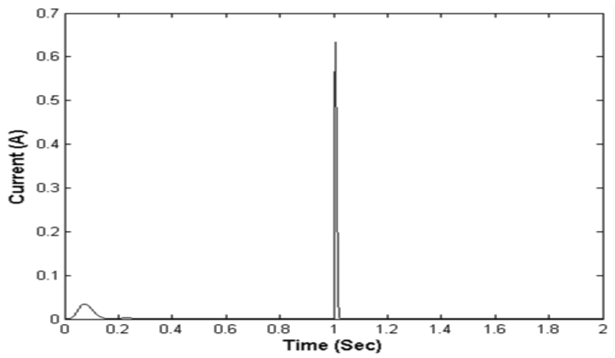

Fig.24. Positive sequence current under overload and rotor fault at 1sec

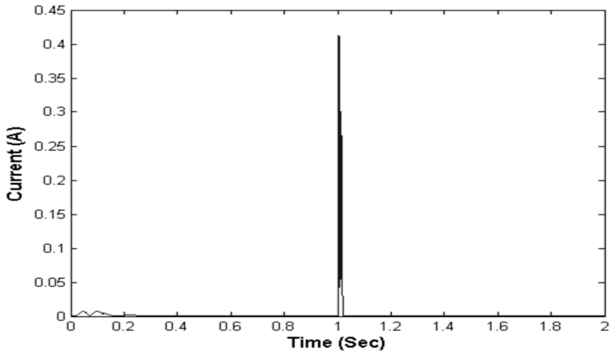

Fig.25. Negative sequence current under overload and rotor fault at 1sec

4. FUZZY BASED FAULT DETECTION

Fig.26 shows the schematic of the proposed fuzzy based fault detection scheme. The faults will introduce the unbalance in the line currents. The winding unbalance injects negative sequence current and voltage in the machine. The sequence currents such as positive (I_{a1}) and negative sequence (I_{a2}) currents are calculated from line currents which are expressed as follows,

$$I_{a1} = \frac{1}{3}\left[I_{as} + \alpha I_{bs} + \alpha^2 I_{cs} \right] \quad (8)$$

$$I_{a2} = \frac{1}{3}\left[I_{as} + \alpha^2 I_{bs} + \alpha I_{cs} \right] \quad (9)$$

where, $\alpha = -0.5+j0.866$ and $\alpha^2 = -0.5-j0.866$

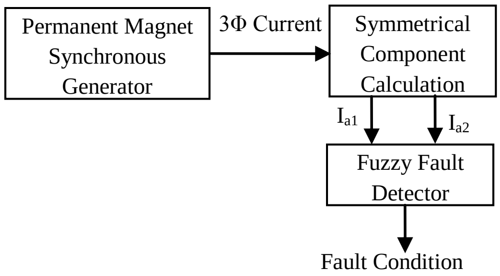

Fig.26. Schematic of proposed scheme

The model based fuzzy fault detecting system consists of three basic steps, namely parameter generation, parameter evaluation and fault presentation.

4.1 PARAMETER GENERATION

The mathematical model of the system is used to generate the sequence component such as positive sequence current and negative sequence current from line currents under normal and faulty conditions. These sequence components are affected by every specified fault which is given as the input to the fuzzy system.

4.2 FUZZY BASED PARAMETER EVALUATION

The range of membership functions for the input and output parameters are shown in Fig.27(a) and Fig.27(b). The trapezoidal membership function with inconsistent width is used for constructing input variables and the Takagi-Sugeno singleton linear model is used to create the output membership function. The positive sequence and negative sequence current are constructed using 11 membership functions and 14 membership functions respectively. The rules are framed based on the variation in sequence current component for different types of fault using expert knowledge. Fig.28 shows the simulation model for fuzzy based fault detection system with positive sequence current and negative sequence current as input and seven different conditions as output. The 36 rules are framed based on occurrences of fault in fuzzy inference system.

Table.1. Ranges of positive sequence current (I_{a1}) based on different faults

MF	Left Corner (LC)	Peak Point1 (PP1)	Peak Point2 (PP2)	Right Corner (RC)	Condition
1	2.5e-007	3e-007	7.5e-007	7.5e-007	RB
2	6e-007	6.1e-007	7.7e-007	7.7e-007	NO
3	7.7e-007	7.7e-007	2.838e-006	2.839e-006	RB, NO
4	2.837e-006	2.838e-006	3.463e-006	3.464e-006	OL & RB
5	3.462e-006	3.463e-006	4.4e-006	4.41e-006	RB, NO
6	4.4e-006	4.41e-006	5.6e-006	5.61e-006	NO
7	5.618e-006	5.628e-006	5.63e-006	5.64e-006	OL, L-G
8	6.95e-006	6.95e-006	3.784e-005	3.8e-005	L-G
9	0.023	0.02386	0.5342	0.54	L-L-G
10	5.6e-006	5.75e-006	5.79e-006	5.8e-006	EF
11	5.8e-006	5.894e-006	8.2e-006	8.2e-006	OL

Table.2. Ranges of negative sequence current (I_{a2}) based on different faults

MF	Left Corner (LC)	Peak Point 1 (PP1)	Peak Point 2 (PP2)	Right Corner (RC)	Condition
1	7e-010	7e-010	1.6e-009	1.6e-009	RB
2	8.5e-010	8.5e-010	1.36e-009	1.36e-009	NO
3	1.126e-009	1.127e-009	1.99e-009	1.99e-009	OL
4	1.44e-009	1.442e-009	1.446e-009	1.446e-009	NO
5	1.688e-009	1.689e-009	2.1e-009	2.12e-009	NO
6	2.05e-009	2.1e-009	2.49e-009	2.49e-009	RB
7	2.44e-009	2.44e-009	5.1e-009	5.1e-009	NO
8	2e-009	2e-009	5.265e-009	5.266e-009	OL & RB, OL
9	5.26e-009	5.265e-009	9.9e-009	9.9e-009	OL
10	1e-008	1.025e-008	1.733e-008	1.8e-008	MECH
11	1.7e-006	1.739e-006	5.748e-006	5.8e-006	L-G
12	1e-005	1.11e-005	2.387e-005	2.4e-005	L-G
13	0.023	0.02386	0.5342	0.54	L-L-G
14	3.94e-009	3.94e-009	3.959e-009	3.96e-009	EF

Table.3. Rules in fuzzy fault detector

Conditions	Positive Sequence Current (Ia1)	Negative Sequence Current (Ia2)
Normal Operation	2,3,5,6	2,4,5,7
Over Load	7,11	3,8,9
Rotor Breakage	1,3,5	1,6
Mechanical Fault	-	10
Line to Ground Fault	7,8	11,12
Double Line to Ground Fault	9	13
Electrical Fault	10	14
Rotor Breakage & Over Load	4	8

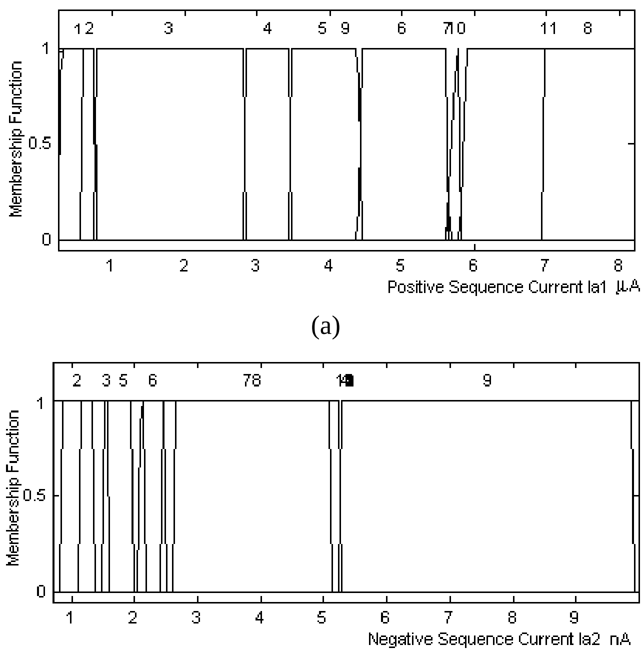

Fig.27. Membership functions of inputs to the fuzzy system

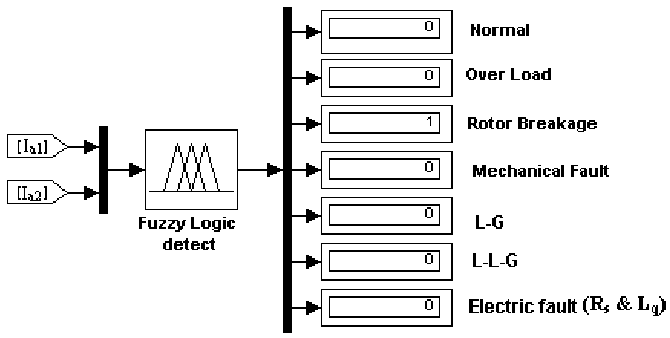

Fig.28. Fuzzy fault diagnosis system

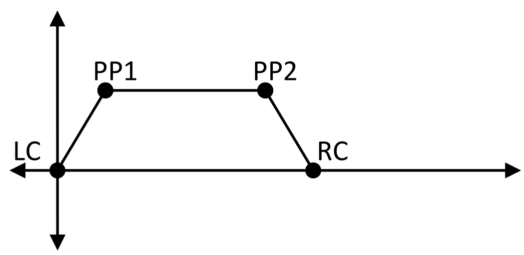

Fig.29. Trapezoidal membership function

Fig.29 shows the description of trapezoidal membership function which consist of Left Corner (LC), Peak Point1 (PP1), Peak Point 2 (PP2) and Right Corner (RC). The ranges of membership functions for positive and negative sequence currents under various fault conditions respectively are presented in Table.1 and Table.2. Table.3 shows the evaluation of rule base of membership function for I_{a1} and I_{a2} to represent various faults. The 36 rules are fired for the specific change in sequence current component and faults are detected.

4.3 FAULT REPRESENTATION

The occurrence of the fault conditions are classified as follows

1. φ^1 = [1 0 0 0 0 0 0] represents, if the input variables correspond to nominal operating conditions.
2. φ^2 = [0 1 0 0 0 0 0] represents, if the input variables correspond to overload condition.
3. φ^3 = [0 0 1 0 0 0 0] represents, if the input variables correspond to rotor fault.
4. φ^4 = [0 0 0 1 0 0 0] represents, if the input variables correspond to a mechanical fault
5. φ^5 = [0 0 0 0 1 0 0] represents, if the input variables correspond to L-G Fault
6. φ^6 = [0 0 0 0 0 1 0] represents, if the input variables correspond to L-L-G Fault
7. φ^7 = [0 0 0 0 0 0 1] represents, if the input variables correspond to electrical fault (Variation of r_s and L_q)
8. φ^8 = [0 1 1 0 0 0 0] represents, if the input variables correspond to rotor fault-over load.

Thus for a specific set of input variable, the faults are detected using a fuzzy based detection scheme.

5. CONCLUSION

The fuzzy fault detector has been proposed to detect various possible faults which are likely to occur in permanent magnet synchronous generator by monitoring sequence current components. The fuzzy fault detector is designed by creating the fuzzy inference system and rule base was evaluated relating sequence current component to the type of faults. These rules are fired for specific changes in sequence current component and corresponding faults was detected using expert knowledge. It has been observed that the fuzzy fault detector detects the fault to the greatest extent with minimum number of rules.

Appendix [I]

Specification of PMSG

No. of phases	3
No. of poles	4
Rated Voltage (V)	40 V
Rated Current (A)	3.98 A
Rated Power (P)	135 W
Power Factor	0.85 (lag)
Stator Resistance (r_s)	0.5 Ω
Self Inductance (L_{ss})	0.01 H
Flux Linkage (Ψ_m)	0.054 N-m-A^{-1}
Viscous Friction co-efficient	0.00006 N-m-s-rad^{-1}
Moment of Inertia (J)	0.0075 Kg-m^2
Rated Speed (ω)	399 rad-s^{-1}
Model	23 NEMA Size H234-G

REFERENCES

[1] Sergey Edward Lyshevski, "*Electromechanical Systems, Electric Machines, and Applied Mechatronics*", CRC Press, 1999.

[2] Kai Zhang, Hossein M. Kojabadi, Peter Z.Wang and Liuchen Chang, "Modeling of a Converter-Connected Six-Phase Permanent Magnet Synchronous Generator", *Proceedings of the International Conference on Power Electronics and Drives Systems*, Vol. 2, pp. 1096-1100, 2005.

[3] Aleksandr Nagorny and Narajan V. Dravid, "High speed Permanent magnet synchronous motor/generator design for flywheel applications", *National research council associateship award*, Cleveland Ohio, 2005.

[4] Sergey Edward Lyshevski and Alberico Menozzi, "Control of Permanent magnet brushless DC motors", *Proceedings of the American Control Conference Arlington*, Vol. 3, pp. 2150-2155, 2001.

[5] B. Dehkordi, A. M. Gole and T. L Maguire "Permanent Magnet Synchronous Machine Model for Real- Time Simulation", *Proceedings of the International Conference on Power Systems Transients (IPST'05)*, Canada, 2005.

[6] G.B. Kliman, W.T. Premerlati, R.A. Roegl and D. Hoeweler, "A new approach to on line fault detection in AC motors", *IEEE Conference on Industry Applications*, Vol. 1, pp. 687-693, 1996.

[7] J. Sottile and J. K. Kohler, "An on-line method to detect incipient failure of turn insulation in random-wound motors", *Proceedings of IEEE Transactions on Energy Conversion*, Vol. 8, No. 4, 1993.

[8] J. Penman, H. G. Sedding, B. A. Lloid, and W. T. Fink, "Detection and location of inter-turn short circuits in the stator windings of operating motors", *Proceedings of IEEE Transactions on Energy Conversion*, Vol. 9, No. 4, pp. 652-658, 1994.

[9] H Jiang, R Aggarwal, G Weller, S Ball and L Denning, "A new approach to synchronous generator internal fault simulation using combined winding function theory and direct phase quantities", *Ninth International Conference on Electrical Machines and Drives*, pp. 105-111, 1999.

[10] Gojko M. Joksimovic and Jim Penman, "The Detection of Inter-Turn Short Circuits in the Stator Windings of Operating Motors", *IEEE Transactions on Industrial Electronics*, Vol. 47, No. 5, pp. 1078-1084, 2000.

[11] Amol S. Kulkarni *et al.*, "Development of a Technique for On-Line Detection of Shorts in Field Windings of Turbine-Generator Rotors: Circuit Design and Testing", *IEEE Transactions on Energy Conversion*, Vol. 15, No. 1, pp. 8-13, 2000.

[12] Tommy W.S. Chow and Hong-Zhou Tan, "HOS-based nonparametric and parametric methodologies for machine

fault detection", *IEEE Transactions on Industrial Electronics*, Vol. 47, No. 5, pp. 1051-1059, 2000.

[13] Dawei Xiang, Li Ran, Peter J. Tavner and Schunchang Yang, "Control of doubly fed induction generator in a wind turbine during grid fault ride-through", *IEEE Transaction on Energy conversion*, Vol. 21, No. 3, pp. 652-662, 2006.

[14] Rolf Isermann, "On Fuzzy Logic Applications for Automatic Control, Supervision, and Fault Diagnosis", *IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans*, Vol. 28, No. 2, pp. 221-235, 1998.

[15] Rolf Isermann, "*Fault diagnosis system- An introduction from fault detection to fault tolerance*", Berlin, Springer, 2006.

[16] N. Selvaganesan, D. Raja and S. Srinivasan, "Fuzzy based fault detection and control for 6/4 switched reluctance motor", *Iranian Journal of Fuzzy Systems*, Vol.4, No.1, pp. 37-51, 2007.

[17] Li Liu and David A. Cartes, "On-line identification and robust fault diagnosis for nonlinear PMSM drives", *Proceedings of the American Control Conference*, Vol. 3, pp. 2023-2027, 2005.