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Energy Procedia 74 (2015) 1323 – 1336
Energy Procedia

International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES15

Open-circuit and inter-turn short-circuit detection in PMSG for wind turbine applications using fuzzy logic.

A. Bechkaoui[a,*],A.Ameur[b], S. Bouras[c] and A. Hadjadj[d]

[a,c]*Department of electromechanical Engineering, Annaba University*
[b,d]*Department of Electrical Engineering, Laghouat University*

Abstract

On line monitoring of PMSG for wind turbine is becoming increasingly important. Knowledge based fuzzy logic approach helps in diagnosing the PMSG for wind turbine faults. The current work presents an effective method for diagnosing the stator side faults such as inter-turn short-circuit and open phase. Stator condition is diagnosed based on the stator RMS values of current amplitude in addition to the knowledge expressed in rules and membership function. The model is implemented in MATLAB/SIMULINK with the data obtained under both healthy and faulty condition. The fuzzy system is able to identify the motor stator condition with high accuracy.

Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)

Keywords: Diagnosis;Fuzzy logic ; Permanent magnet synchronous generators;Stator current amplitudes; inter-turn short-circuit.

1. Introduction

Interest in the use of renewable energy is increasing because people are involved in environmental issues. Among renewable, wind power is now widely used [1], [2]. Wind turbines based on a wound rotor induction generator have the disadvantage of using a system of collector rings and brushes and a multiplier, leading to significant maintenance costs particularly for offshore projects located in saline. To limit these drawbacks, some manufacturers

* Corresponding author. Tel.: +213670141223; fax: +21329421616.
*E-mail address:*amaramour73@yahoo.com

1876-6102
Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)
doi:10.1016/j.egypro.2015.07.779

have developed wind turbines based on large synchronous machines in number of pole pairs and coupled directly to the turbine, thus avoiding the multiplier. [3] In addition the generator is provided with permanent magnets (the DC excitation circuit replaced by P.M), the system of slip ring and brushes are eliminated. By eliminating the brushes, the PMSG has a smaller physical size, a low moment of inertia which means a higher reliability and power density per volume ratio. Also by having permanent magnets in the rotor circuit, the electrical losses in the rotor are eliminated. Due to the mentioned advantages, the PMSG are becoming an interesting solution for wind turbine applications which are compared to other types of DC machines, synchronous with electrical excitation and asynchronous generator many advantages, among others, low inertia and high power density and efficiency,

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 [4],[5].

This paper applies fuzzy logic, to the diagnosis of PMSG for wind turbine stator and phase conditions, based on the amplitude features of stator currents. This method has been chosen because fuzzy logic has proven ability in mimicking human decisions [6]. The generator condition is described using linguistic variables. Fuzzy subsets and the corresponding membership functions describe stator current amplitudes. A knowledge base, comprising rule and data bases, is built to support the fuzzy inference. The obtained results indicate that the fuzzy logic approach, as proposed by the authors, is capable of highly accurate diagnosis.

2. Faulty PMSG model for inter-turn short-circuit detection

The faulty PMSG model used for inter-turn short-circuit detection is based on a former study [7] with less modelling assumptions (voltage drops due to short-circuit reduction is taken into account) to make the PMSG model more sensitive to windings faults. The model enables the fault localization with the use of angle θ_{cc} (equal to 0, $2\pi/3$ or $4\pi/3$ for a short-circuit respectively on phase A, phase B or phase C) and the number of short-circuit turns ns/c (ratio between short-circuited turns and the whole turns on a stator winding). Figure 1 shows the basic model for fault diagnosis with inter-turn short-circuit on phase C ($\theta_{cc} = 4\pi/3$).

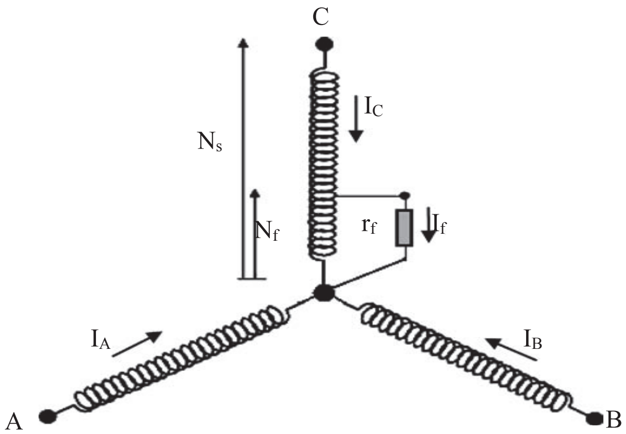

Fig. 1.Three phase stator winding with turn fault in phase "C"

Setting up the mesh equations for the circuit in Fig. 1 will express the voltage equations as:

$$[\mathrm{V_s}] = -R_s[I_s] - L\,\frac{d\,[I_s]}{dt} + [E_s] - N_{cc}R_sT_{s/c}I_f - \sqrt{\frac{3}{2}}N_{cc}L_{ps}T_{32}\begin{bmatrix}\cos(\theta_{cc})\\ \sin(\theta_{cc})\end{bmatrix}\frac{d[I_f]}{dt} - N_{cc}L_sT_{s/c}\,\frac{d[I_f]}{dt} \qquad (1)$$

Where [Vs], [Is] and [Es] are the stator voltage, current and electromotive forces vector:

$$[\mathrm{V_s}] = [v_{as} \quad v_{bs} \quad v_{cs}]^T$$

$$[I_s] = [i_{as} \quad i_{bs} \quad i_{cs}]^T$$

$$[E_s] = [e_{as} \quad e_{bs} \quad e_{cs}]^T \qquad (2)$$

$R_s$is the phase resistance and [L] is the inductance matrix of the healthy PMSG respectively:

$$[\mathrm{L}\ ] = \begin{bmatrix} L_{ls}+L_{ps} & \frac{-L_{ps}}{2} & \frac{-L_{ps}}{2} \\ \frac{-L_{ps}}{2} & L_{ls}+L_{ps} & \frac{-L_{ps}}{2} \\ \frac{-L_{ps}}{2} & \frac{-L_{ps}}{2} & L_{ls}+L_{ps} \end{bmatrix} \qquad (3)$$

Where :

$L_s = \frac{3}{2}L_{ps} + L_{ls}$ stator synchronous inductance.

The voltage equation of the faulty loop (c_{s2}) is:

$$0 = N_{cc}R_sT_{s/c}{}^T[I_s] + \sqrt{\frac{3}{2}}N_{cc}L_{ps}\left(T_{32}\begin{bmatrix}\cos(\theta_{cc})\\ \sin(\theta_{cc})\end{bmatrix}\right)^T\frac{d[I_s]}{dt} - N_{cc}T_{s/c}{}^T[E] + N_{cc}R_sI_f \qquad (4)$$

$$[T_{32}] = \frac{1}{\sqrt{3}}\begin{bmatrix} \sqrt{2} & 0 \\ \frac{-1}{\sqrt{2}} & \sqrt{\frac{3}{2}} \\ \frac{-1}{\sqrt{2}} & -\sqrt{\frac{3}{2}} \end{bmatrix}$$ Concordia transformation matrix

Short–circuit matrix:

$$[T_{s/c}] = \frac{1}{3}\begin{bmatrix} 1+2\cos(\theta_{cc}) \\ 1+2\cos\left(\theta_{cc}-\frac{2\pi}{3}\right) \\ 1+2\cos\left(\theta_{cc}-\frac{4\pi}{3}\right) \end{bmatrix} \left(= \begin{bmatrix}1\\0\\0\end{bmatrix} if\ \theta_{cc}=0; = \begin{bmatrix}0\\1\\0\end{bmatrix} if\ \theta_{cc}=\frac{2\pi}{3}; = \begin{bmatrix}0\\0\\1\end{bmatrix} if\ \theta_{cc}=\frac{4\pi}{3} \right) \tag{5}$$

The expression of the electromagnetic torque (T_e) and the mechanical equation are given as follows:

$$T_e = \frac{[E_s]\,[I_s] - e_{a2}i_f}{\Omega}$$
$$T_e - T_l = J\frac{d\Omega_r}{dt}. \tag{6}$$

Where J is the moment of inertia and T_l is the load torque. Ω_r is the mechanical angular speed.

3. Stator condition Monitoring Using Fuzzy Logic

This paper applies fuzzy logic of wind turbine using PMSG fault detection and diagnosis. The generator condition is described using linguistic variables. Fuzzy subsets and the corresponding membership functions describe stator current amplitudes. A knowledge base, comprising rule and data bases, is built to support the fuzzy inference (figure. 2). The PMSG condition is diagnosed using a compositional rule of fuzzy inference.

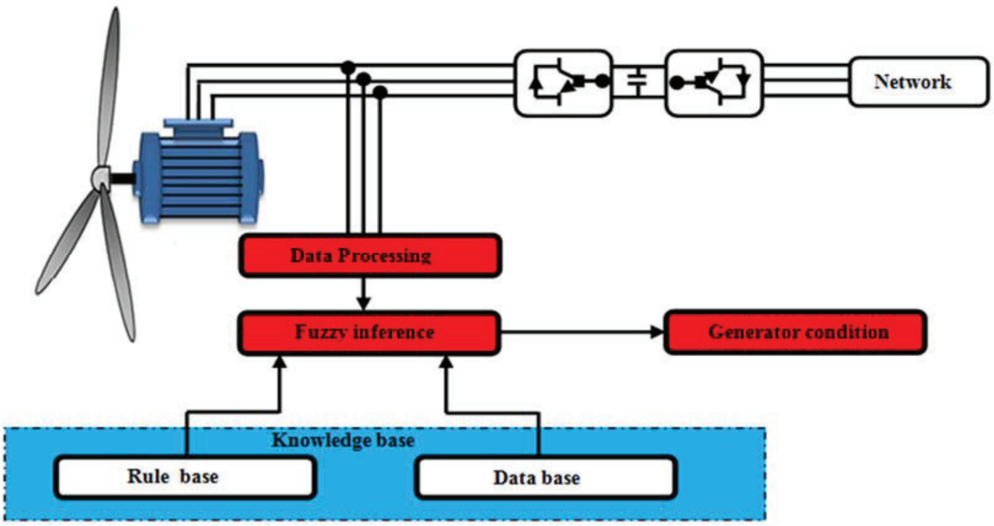

Fig. 2: Block diagram of motor condition monitoring system.

3.1. Fuzzy System Input-Output Variables

In this case, the stator current amplitudes ia, ib and ic are considered as the input variables to the fuzzy system. The stator condition, cm, is chosen as the output variable. All the system inputs and outputs are defined using fuzzy set theory. For instance, the term set t (cm), Where each term in t (cm) is characterized by a fuzzy subset, in a universe of discourse cm. Healthy (Good), Open phase A(OPA), Open phase B(OPB), Open phase C(OPC), Incipient defect (ID), Defect (DF) and Sever defect (SD) . Similarly, the input variables ia, ib, and ic are interpreted as linguistic variables, with, t (Q) = {zero, small, medium, big, very big}. Where Q= Ia, Ib,Ic Respectively. Fuzzy membership functions for the both input linguistic variables and output linguistic variables are shown below.

3.2 Membership Functions

Based on the RMS data obtained under different fault conditions, the membership functions and corresponding limits are assigned for both input linguistic variables and the output linguistic variables. Fuzzy membership functions for the both input linguistic variables and output linguistic variables are shown below.

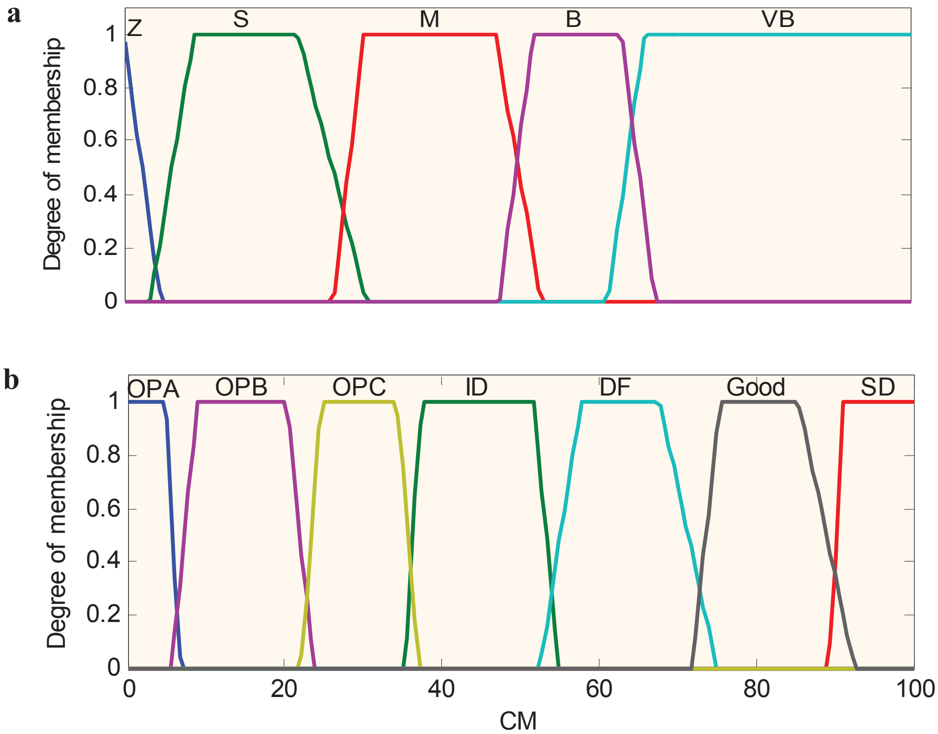

Fig. 3.(a) Membership functions for the input variables; (b) Membership functions for the output variables

Fig.3.(a) shows the membership function for the input linguistic variables where the RMS stator of three phase currents Ia, Ib, Ic are the inputs to the fuzzy system and the output stator condition with : Good condition (Good), Open phase A (OPA), Open phase B (OPB), Open phase C (OPC), Incipient defect (ID), Defect (DF) and Sever defect (SD) Shown in above Fig.3.(b).

3.2. Rule Base

For Our Study, We Have Obtained The Following 17 If-Then Rules.

Table-1: Rule base for Motor Health

Rule	If Ia is	And Ib is	Ad Ic is		Motor condition
1	Z	None	None		OPA
2	None	Z	None		OPB
3	None	None	Z		OPC
4	S	S	S		Good
5	M	M	M		Good
6	S	S	M		ID
7	S	M	S		ID
8	S	M	M		ID
9	M	M	B		DF
10	M	B	M	THEN	DF
11	M	B	B		DF
12	B				DF
13	None	B			DF
14	None	None	B		DF
15	VB	None	None		SD
16	None	VB	None		SD
17	None	None	VB		SD

Tabel 2. Output Relationship between short circuit and winding condition

Winding Condition	Short Circuit (%)
Good	0%
Incipient defect	0< Short Circuit ≤ 6
Defect	6< Short Circuit ≤16
Sever defect	Short Circuit>16

4. Simulation and Results

Three phases PMSG parameters: R_s=1.4 Ω, ij=0.154wb, L_d =6.6mH, L_q =5.8mH F=0.00038N.m.s/rad, J=0.00176 kg.m2 [8].

Fig 1. (a) and (b) shows respectively: the Stator currents of wind turbine for PMSG under healthy condition and output controller. From these results it can be concluded that after the transient period is over, the health of the motor appeared to be "Good" as highlighted in Fig. 1.

Fig. 2 (a) and (b) shows the Stator current and output controller for open phase. From these results it can be concluded that during normal operation (before fault) the health of the generator is implied as "Good". As soon as the fault is created (Open phase (A),RMS Ia=0) , and the health of the wind turbine for PMSG goes to Open phase, It is perceptible distinctly form waveforms corresponding to the generator condition.

Fig (3-5) shows the results obtained from performed simulations in the process of different number of short circuits faults in stator winding. From the above result, it is concluded that, this is of great practical use as motor be protected from the total damage and hence the complete breakdown of PMSG.

The RMS values of stator currents are applied to the fuzzy logic controller and the corresponding fuzzy logic rule viewer under different motor conditions are shown in the Figures 6-8. Figure 6(a) Shows the result of fuzzy detection circuit under healthy condition with an output value of 81.4 based on the input stator currents.

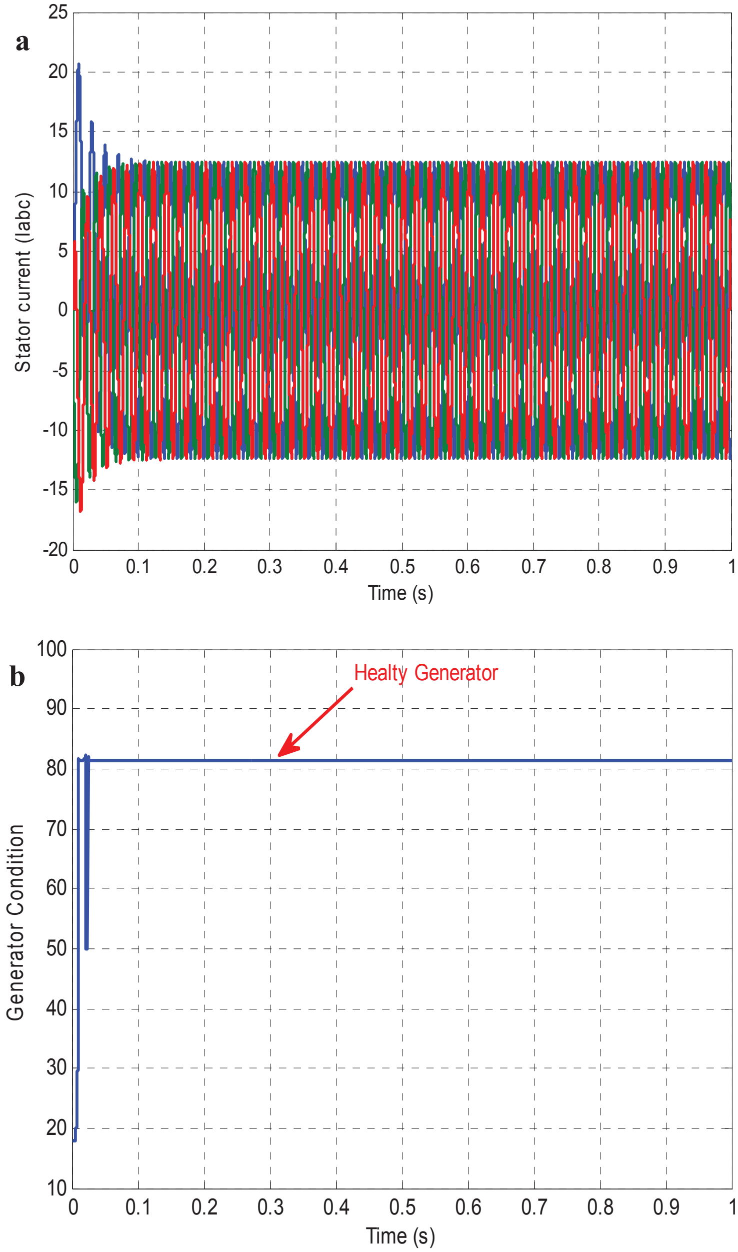

Fig 1. (a)Stator currents of wind turbine for PMSG under healthy condition ;(b) output controller for healthy

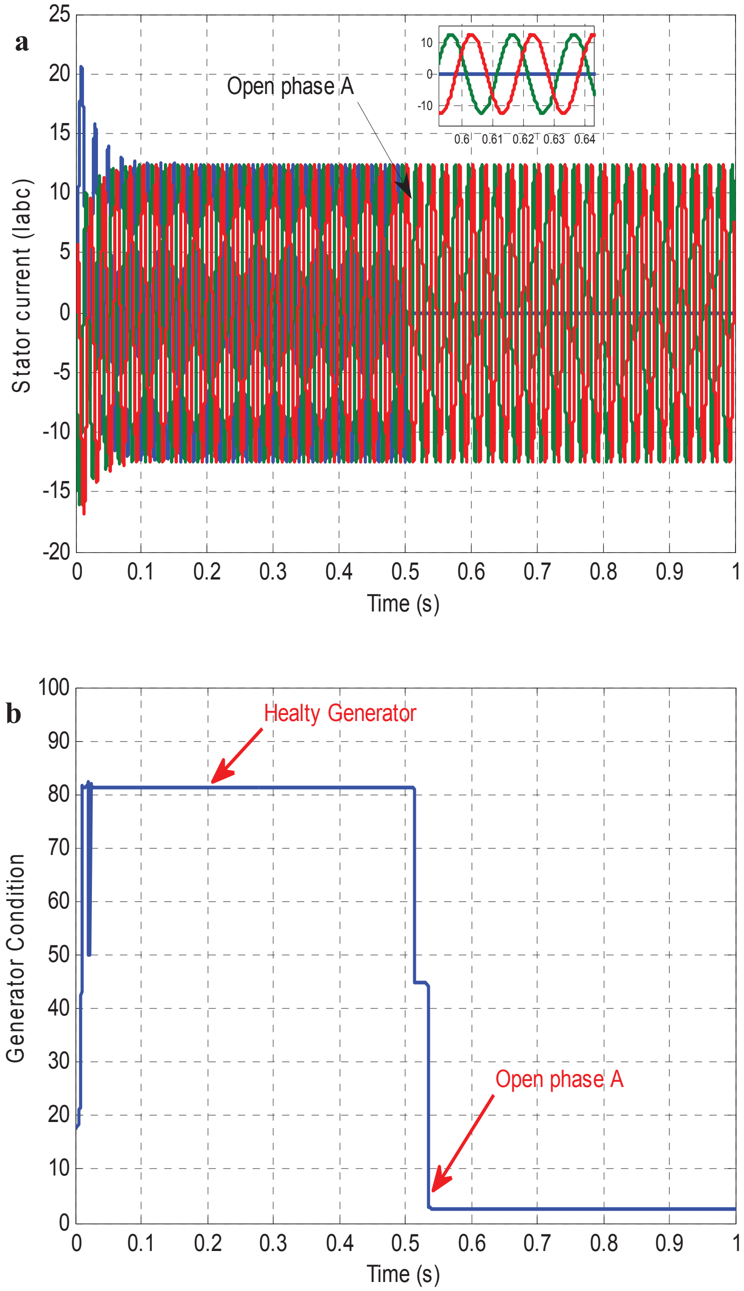

Fig 2. (a)Stator currents of wind turbine for PMSG under open phase A ;(b) output controller for open phase A

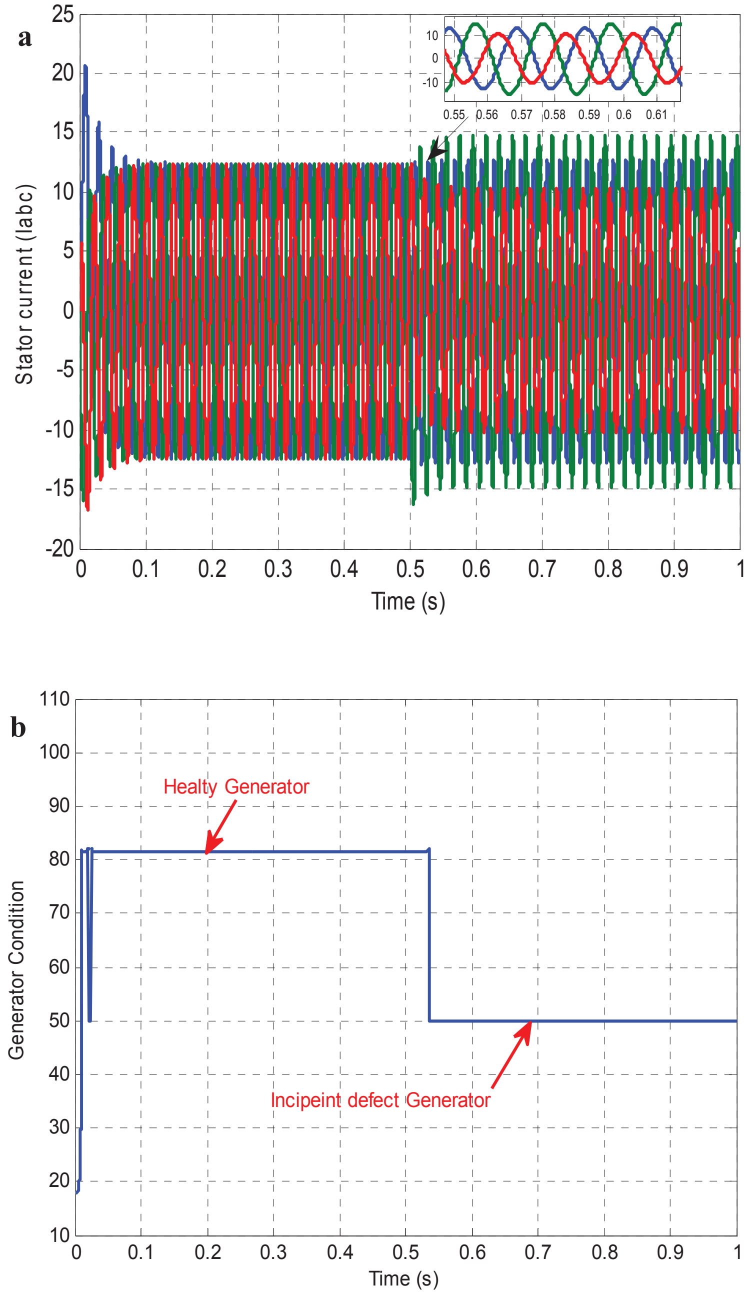

Fig 3. (a)Stator currents of wind turbine for PMSG incipient defect stator ;(b) output controller incipient defect stator

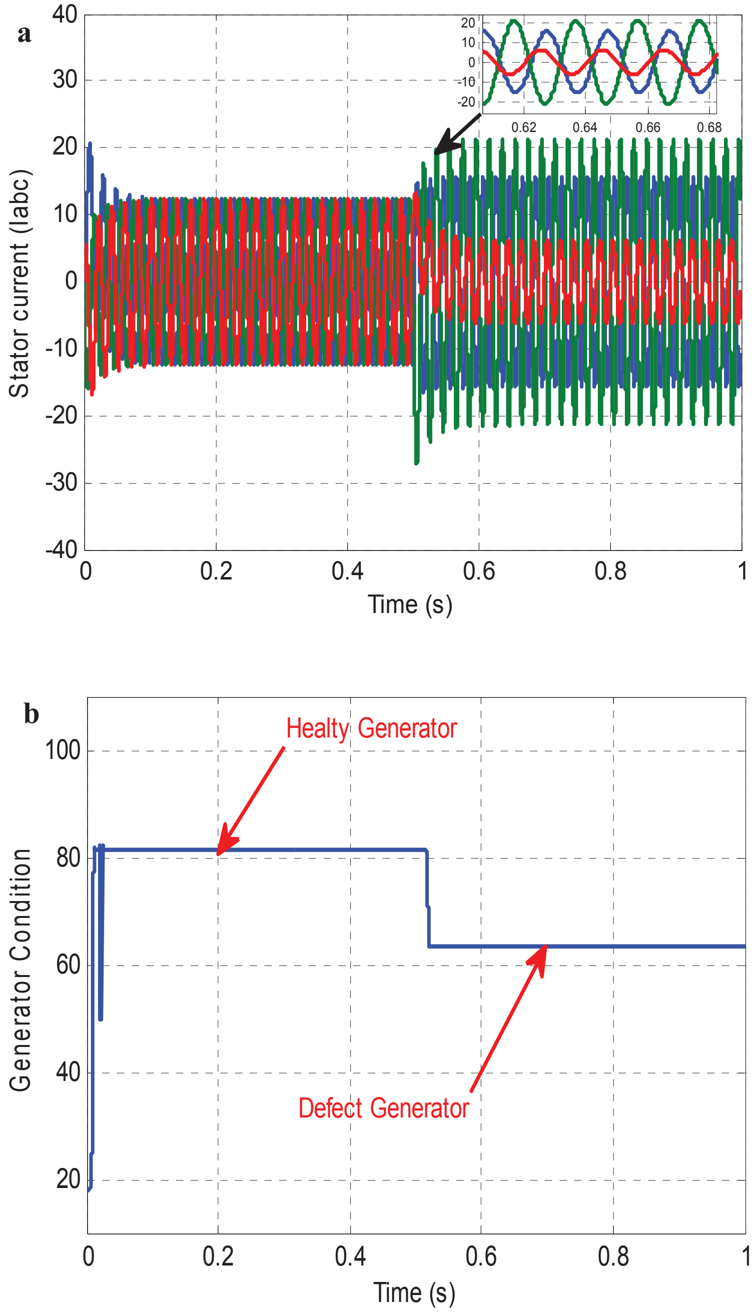

Fig 4. (a)Stator currents of wind turbine for PMSG under defect stator ;(b) output controller for defect stator

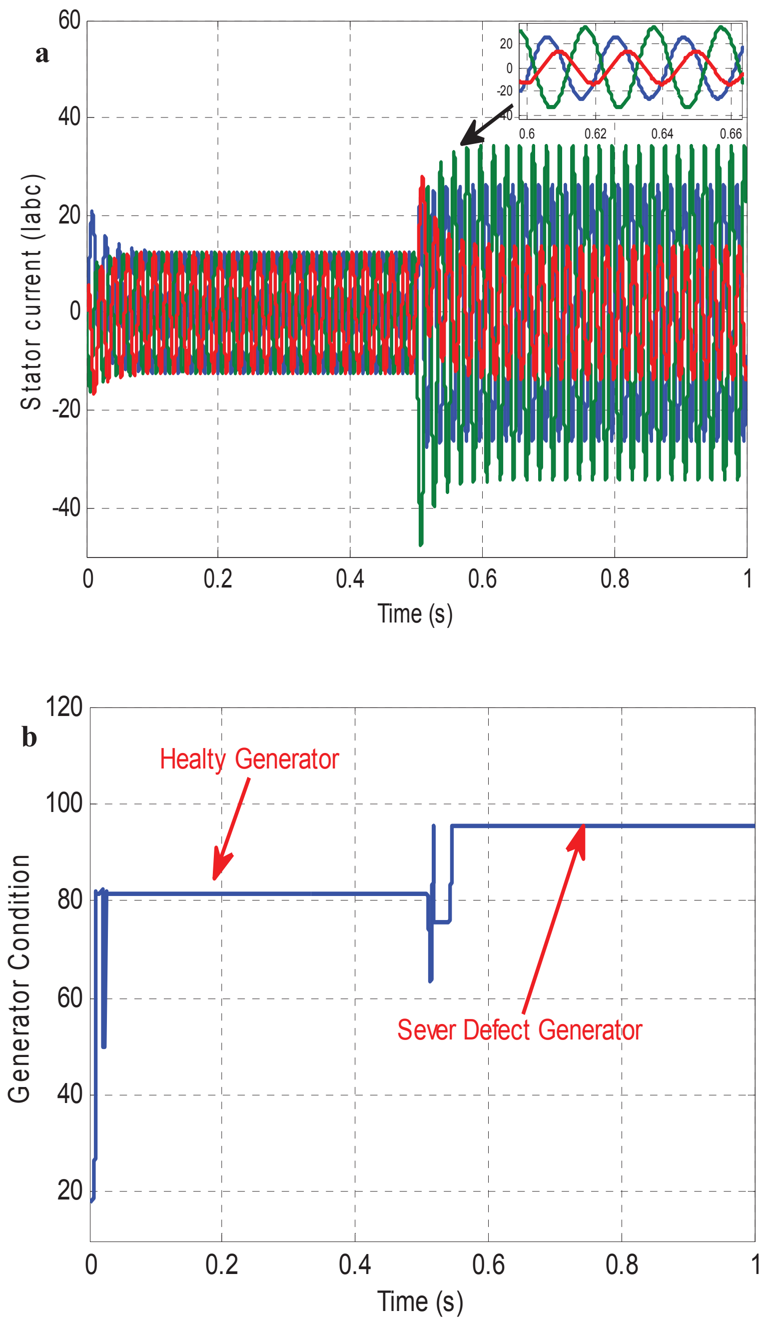

Fig 5. (a)Stator currents of wind turbine for PMSG under sever defect stator ;(b) output controller for sever defect stator

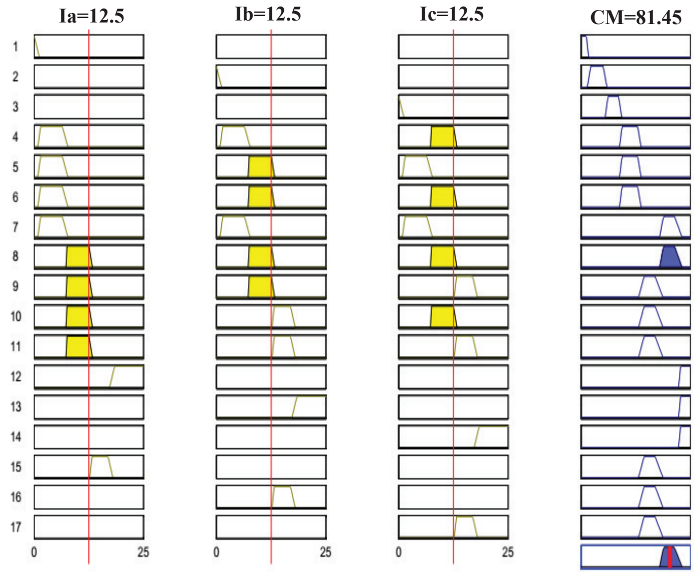

Fig 6. Fuzzy inference diagram under healthy condition

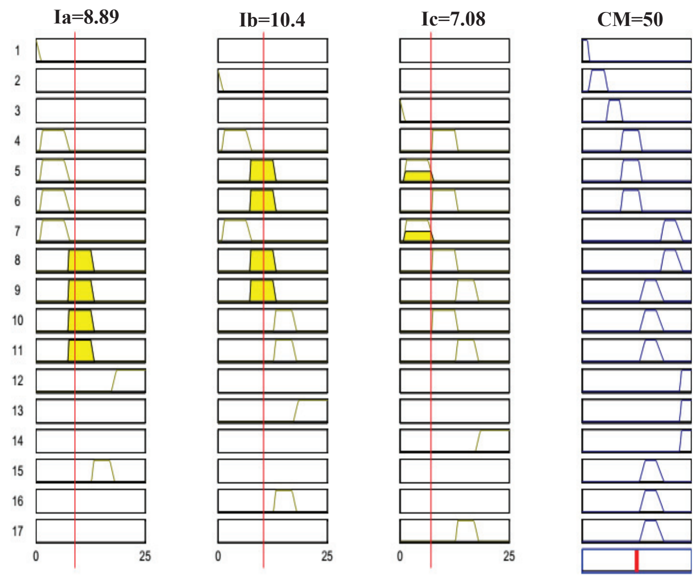

Fig 7. Fuzzy inference diagram under incipient defect stator condition

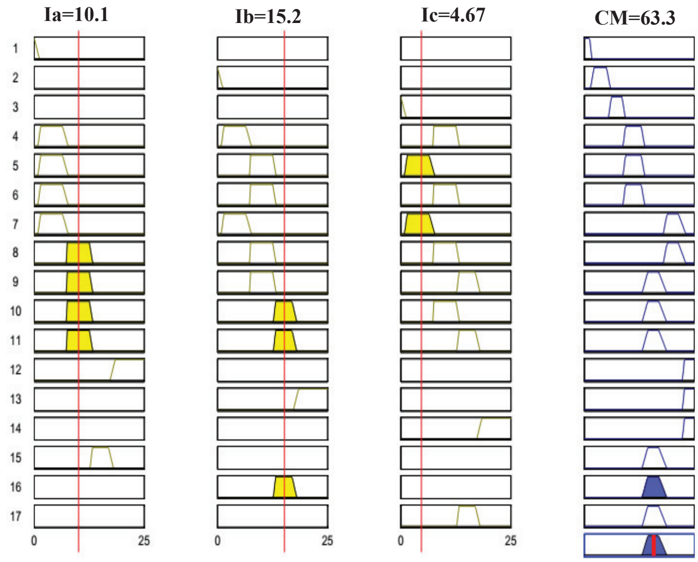

Fig 8. Fuzzy inference diagram under defect stator condition

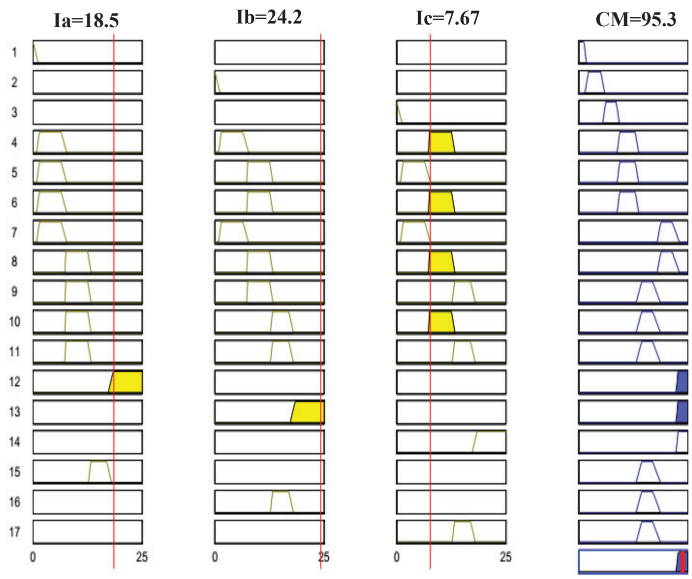

Fig 9. Fuzzy inference diagram under sever defect stator condition

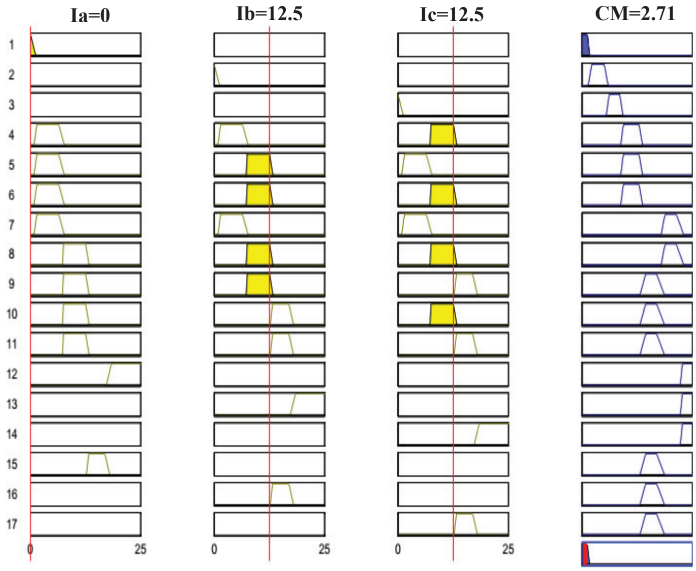

Fig 10. Fuzzy inference diagram under open phase A condition

CONCLUSION

In this paper, the realization of the fault in stator winding of wind turbine using PMSG has been considered. In the first place, the PMSG was simulated by dynamic equations to that effect; afterwards, the equations were revisited by accounting faults in one of the phases. As for the issue of fault realization, the fuzzy logic and its application in clustering have been used. As an advantage of this method, we can refer to its high accuracy, online state as well as its deprivation from an accurate model for the system; however, it should be noted that its capability of being adjusted to various conditions of a motor is among the extremely practical advantages of such method in modern industry; which means that we are able to meet the requirements of the objective through making a slight change in the mechanism of fault realization in case motor parameters undergo changes at any respect.

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