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Condition Monitoring and Fault Detection in Wind Turbine Based on DFIG by the Fuzzy Logic

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Abstract

Doubly-fed induction generator is widely used in wind turbine conversion systems. Several research works are being made to efficiently approve existing condition monitoring and fault detection techniques for these systems. The condition monitoring of these systems becomes more and more important, the main obstacle in this task is the lack of an accurate analytical model to describe a faulty DFIG in the majority of the research tasks. In this paper, we present the monitoring strategy of short-circuit fault between turns of the stator windings and open stator phases in doubly-fed induction generator by fuzzy logic technique. The stator condition monitoring is diagnosed based on the root mean square values of current magnitude in addition to the knowledge expressed in rules and membership function. The proposed strategy is verified using simulations performed via the model of Doubly-fed induction generator built in MatLab ® SIMULINK.

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Keywords: Wind turbine, DIFG, Monitoring, Detection fault, Fuzzy logic.

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1. Introduction

Wind energy installations based on doubly-fed induction generators (DFIG) take an important place in the world of production of electric energy, because of the robustness of this machine in such installations types, the increase interest of wind energy has been accompanied by efforts to improve reliability, effective condition monitoring and better efficiency [1, 2].

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The condition monitoring and fault detection are important in energy conversion systems to avoid serious consequences because any fault is potentially able to impact the total system behavior with higher operation costs and shutdown of electrical energy production [3-5].

Generally, the DFIG can be external or internal fault. For the external faults, they are caused by the feeding source (the rotor feeding), the mechanical load, and the machine use environment. The intern faults are caused in the magnetic circuits, stator and/or rotor windings, the air-gap, and the machine cage rotor. Within this framework, the statistics reveal that the electrical faults on the level of the stator are the most recurrent [6-8].

Nevertheless, through this work, electrical faults will be well interested, particularly in the short-circuit faults between stator turns and the open stator phases faults of the (DFIG).

The short circuit inter-turn fault of stator windings usually starts as an undetected insulation failure between two adjacent turns. As a result, it slowly develops to a short circuit isolating a number of turns. In some cases, the fault occurs due to an electric arc connecting two points of the winding [9, 10].

The open stator phases are caused by several origins. This fault causes are the cancellation of the current in the phase failing, the unbalanced of the currents in other phases and the significant undulation of torque. These consequences are less serious than a short-circuit fault since it does not have of problem of heating which can deteriorate the remainder of the machine, but it remains a fault which disturbs the generator function in the supply mode of electrical power energy [11, 12].

The novel diagnosis techniques of energy conversion system have widely used the condition-based maintenance strategies to reduce unexpected failures and downtimes. These techniques have progressed from traditional methods to artificial intelligence based on fuzzy logic system, artificial neural network or combined structure techniques. These techniques have many advantages compared to conventional fault diagnostic approaches [13-15].

Therefore, the proposed approach in this paper is based on the artificial intelligence (fuzzy logic), in the aim to increase the efficiency and the reliability of the diagnosis in the supervision field and diagnosis of the DFIG [16-18]. The model based on artificial intelligence approach as well as the global model are implemented by using software MatLab ® SIMULINK and the obtained results by simulations at healthy function case, short-circuit and open stator phases faults will be mainly represented and interpreted.

2. Modeling of the healthy DFIG

A. Mechanical system modeling

A.1. Turbine modeling

The relation (1) presents the specific speed (λ) to characterize the aerodynamic performance of a wind turbine [19]:

$$\lambda = \frac{R\Omega_t}{V} \qquad (1)$$

With;

Ω_t: angular velocity of turbine rotation;

R: radius of the turbine;

V: wind speed.

The output power (P_g) is given by the following equation:

$$P_g = \frac{1}{2} C_p(\lambda, \beta).\rho.\pi.R^2.V^3 \qquad (2)$$

Where, the power coefficient (C_p) is given by the following relationship [20]:

$$C_p(\lambda, \beta) = C_1[(C_2.a - b) - C_3.\beta - C_4)]e^{-c_6(a-b)} + C_6\lambda \qquad (3)$$

With;

$$a = \frac{1}{\lambda + 0.08\beta} \quad \text{and} \quad b = \frac{0.035}{\beta^3 + 1}$$

$C_1 = 0.5109$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$.

A.2. Gear box modeling

The gear box adjusts the slow speed of the turbine (Ω_t) to the generator fast speed (Ω_g). It is mathematically presented by the following equation:

$$G = \frac{\Omega_g}{\Omega_t} \tag{4}$$

A.3. Transmission shaft Modeling

The transmission shaft model proposed considering the total inertia (J) consists of turbine inertia (J_t) transferred to the generator rotor (J_g).

$$J = \frac{J_t}{G^2} + J_g \tag{5}$$

Mechanical transmission modeling is:

$$J = \frac{\Omega_m}{dt} = T_g - T_{em} - T_{vis} \tag{6}$$

Where, the viscous torque (T_{vis}) is proportional to the mechanical speed(Ω_m):

$$T_{vis} = f.\Omega_m \tag{7}$$

With;

f: the friction coefficient.

The diagram block of the mechanical system is shown in figure 1.

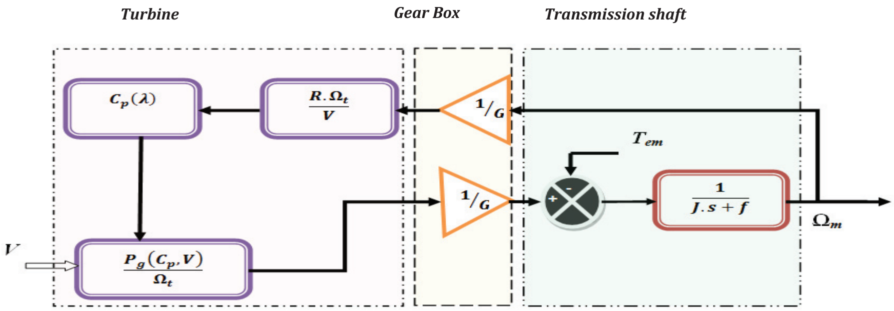


Fig. 1. Diagram of the mechanical system

B. Modeling of double-fed induction generator

Modeling must be performed so that the approach describes clearly the detection method. The voltage stator and rotor equations of a DFIG in synchronous reference can be expressed in the following matrix form [21, 22]:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{bmatrix} \tag{8}$$

Voltage rotor equations:

$$\begin{bmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{bmatrix} = \begin{bmatrix} r_r & 0 & 0 \\ 0 & r_r & 0 \\ 0 & 0 & r_r \end{bmatrix} \begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{ar} \\ \lambda_{br} \\ \lambda_{cr} \end{bmatrix} \tag{9}$$

The flux stator and rotor equations can be expressed in the following matrix form:

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} [L_{ss}] & [L_{sr}] \\ [L_{ss}]^T & [L_{rr}] \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \tag{10}$$

Electromagnetic torque equation:

$$T_{em} = \frac{1}{2}.\begin{bmatrix} \vec{I}_s^t & \vec{I}_r^t \end{bmatrix}.\begin{bmatrix} [L_{ss}] & [L_{sr}] \\ [L_{ss}]^t & [L_{rr}] \end{bmatrix}.\begin{bmatrix} \vec{I}_s \\ \vec{I}_r \end{bmatrix} \tag{11}$$

The inductances matrices are obtained:

$$L_{ss}=\begin{bmatrix} L_{ls+}L_{sm} & -\frac{1}{2}L_{sm} & -\frac{1}{2}L_{sm} \\ -\frac{1}{2}L_{sm} & L_{ls+}L_{sm} & -\frac{1}{2}L_{sm} \\ -\frac{1}{2}L_{sm} & -\frac{1}{2}L_{sm} & L_{ls+}L_{sm} \end{bmatrix} \quad (12)$$

$$L_{sr}=\begin{bmatrix} L_m\sin\theta_r & L_m\sin\left(\theta_r+\frac{2\pi}{3}\right) & L_m\sin\left(\theta_r-\frac{2\pi}{3}\right) \\ L_m\sin\left(\theta_r-\frac{2\pi}{3}\right) & L_m\sin\theta_r & L_m\sin\left(\theta_r+\frac{2\pi}{3}\right) \\ L_m\sin\left(\theta_r+\frac{2\pi}{3}\right) & L_m\sin\left(\theta_r-\frac{2\pi}{3}\right) & L_m\sin\theta_r \end{bmatrix} \quad (13)$$

$$L_{rs}=\begin{bmatrix} L_m\sin\theta_r & L_m\sin\left(\theta_r-\frac{2\pi}{3}\right) & L_m\sin\left(\theta_r+\frac{2\pi}{3}\right) \\ L_m\sin\left(\theta_r+\frac{2\pi}{3}\right) & L_m\sin\theta_r & L_m\sin\left(\theta_r-\frac{2\pi}{3}\right) \\ L_m\sin\left(\theta_r-\frac{2\pi}{3}\right) & L_m\sin\left(\theta_r+\frac{2\pi}{3}\right) & L_m\sin\theta_r \end{bmatrix} \quad (14)$$

$$L_{rr}=\begin{bmatrix} L_{lr+}L_{rm} & -\frac{1}{2}L_{rm} & -\frac{1}{2}L_{rm} \\ -\frac{1}{2}L_{rm} & L_{lsr+}L_{rm} & -\frac{1}{2}L_{rm} \\ -\frac{1}{2}L_{rm} & -\frac{1}{2}L_{rm} & L_{lr+}L_{rm} \end{bmatrix} \quad (15)$$

With;

The mutual inductance of the stator tow-phase winding:

$$L_{sm}=\frac{\mu_0 r\pi l}{g}\left(\frac{N_s}{P}\right)^2 \quad (16)$$

The mutual inductance of the rotor tow-phase winding:

$$L_{rm}=\frac{\mu_0 r\pi l}{g}\left(\frac{N_r}{P}\right)^2 \quad (17)$$

The self mutual inductance of the stator and rotor:

$$L_m=\frac{\mu_0 r\pi l}{g}\left(\frac{N_s}{P}\right)\left(\frac{N_r}{P}\right) \quad (18)$$

Where;
L_{ls}, L_{lr} : are respectively the stator and the rotor leakage inductances;
N_s, N_r : are respectively number of the stator and the rotor turns;
g, P :are respectively thickness of the air-gap and poles number;
l, r: are respectively length and means radius of stator/rotor ;
μ_0 : air permeability.

3. Short-circuit fault of the DFIG model

The development of the diagnosis procedure containing analytical models of the DFIG must cover a certain number of problems of the synthesis methods describing the behavior of the machine, by integrating precisely certain parameters for describing the performance of the generator. The voltage and flows equations of the generator in the presence of the short-circuit faults are [23]:

$$\begin{cases} v_{abcs}=r_s i_{abcs}+\frac{d}{dt}\lambda_{abcs} \\ v_{abcr}=r_r i_{abcr}+\frac{d}{dt}\lambda_{abcr} \\ 0 = r_{cc} i_{cc} + \frac{d}{dt}\lambda_{cc} \end{cases} \quad (19)$$

The flux equations are written in the form:

$$\begin{cases}\lambda_{abcs} = L_{ss} i_{abcs} + L_{rs} i_{abcr} + L_{scc} i_{cc} \\ \lambda_{abcr} = L_{rs} i_{abcs} + L_{rr} i_{abcr} + L_{rcc} i_{cc} \\ \lambda_{cc} = L_{scc} i_{abcs} + L_{rr} i_{abcr} + L_{cc} i_{cc}\end{cases} \tag{20}$$

Where;

λ_{cc}: flux of the phase shorted-circuit;
i_{cc}: currant of the short-circuit phase;
L_{scc}: mutual inductance between a stator phase and short-circuit winding;
L_{rcc}: mutual inductance between a rotor phase and short-circuit winding;

In fault case, we can write inductance of short-circuit winding compared to the stator and rotor phases:

$$L_{cc} = \eta_{cc}^2 (L_m + L_{ls}) \tag{22}$$

The relationship between the turn's number in short-circuits (N_{cc}) and the healthy phase turns number of (N_s) are defined by:

$$\eta_{cc} = \frac{N_{cc}}{N_s} \tag{23}$$

After the transformation of the three-phase system into two-phase (α_s, β_s) the voltage and flow equations become:

$$\begin{cases}\underline{U}_{\alpha\beta s} = R_s \underline{i}_{\alpha\beta s} + \frac{d}{dt}\underline{\lambda}_{\alpha\beta s} \\ \underline{U}_{\alpha\beta r} = R_r \underline{i}_{\alpha\beta r} + \frac{d}{dt}\underline{\lambda}_{\alpha\beta r} - \omega P\left(\frac{\pi}{2}\right)\underline{\lambda}_{\alpha\beta r} \\ \underline{0} = \eta_{cc} R_s \underline{i}_{\alpha\beta s} + \frac{d}{dt}\underline{\lambda}_{\alpha\beta cc}\end{cases} \tag{24}$$

$$\begin{cases}\underline{\lambda}_{\alpha\beta s} = \underline{\lambda}_{\alpha\beta f} + \underline{\lambda}_{\alpha\beta m} = L_f\, \underline{i}_{\alpha\beta s} + L_m\left(\underline{i}_{\alpha\beta s} + \underline{i}_{\alpha\beta r} - \underline{i}_{\alpha\beta cc}\right) \\ \underline{\lambda}_{\alpha\beta r} = \underline{\lambda}_{\alpha\beta m} = L_m\left(\underline{i}_{\alpha\beta s} + \underline{i}_{\alpha\beta r} - \underline{i}_{\alpha\beta cc}\right) \\ \underline{\lambda}_{\alpha\beta cc} = \eta_{cc}. Q.(\theta_{cc}). \underline{\lambda}_{\alpha\beta m}\end{cases} \tag{25}$$

With,

$$Q.(\theta_{cc}) = \begin{bmatrix}\cos^2(\theta_{cc}) & \cos(\theta_{cc})\sin(\theta_{cc}) \\ \cos(\theta_{cc})\sin(\theta_{cc}) & \cos^2(\theta_{cc})\end{bmatrix} \tag{26}$$

$$\begin{cases}\tilde{\underline{i}}_{\alpha\beta cc} = \sqrt{\frac{3}{2}}\eta_{cc}\underline{i}_{\alpha\beta cc} \\ \tilde{\underline{\lambda}}_{\alpha\beta cc} = \sqrt{\frac{3}{2}}\eta_{cc}\underline{\lambda}_{\alpha\beta cc}\end{cases} \tag{27}$$

$\underline{\lambda}_{\alpha\beta m}$: the common magnetizing flux;
$\underline{\lambda}_{\alpha\beta f}$: the stator leakage flux.

The line currents are then the sum of the short-circuit currents and the currents consumed by the traditional model of Concordia. Thus, it becomes possible to express the equation of winding at fault in the reference stator:

$$\tilde{\underline{i}}_{\alpha\beta cc} = \frac{2}{3}\frac{\eta_{cc}}{R_s} Q.(\theta_{cc}). \underline{U}_{\alpha\beta s} \tag{28}$$

4. Stator monitoring using fuzzy logic

4.1. Monitoring system

In this work, the fuzzy logic is used for the monitoring and detection of short-circuit and open stator phase faults in doubly fed induction machine. The diagram block of the suggested approach is shown in figure 2. In this case, linguistic variables, fuzzy subsets and the membership functions describe of the root mean square (RMS) values of current magnitude.

An inference fuzzy system comprising the rules and the data bases is established to support the fuzzy inference. The state of the DFIG is diagnosed by using a compositional rule of fuzzy execution [24, 25].

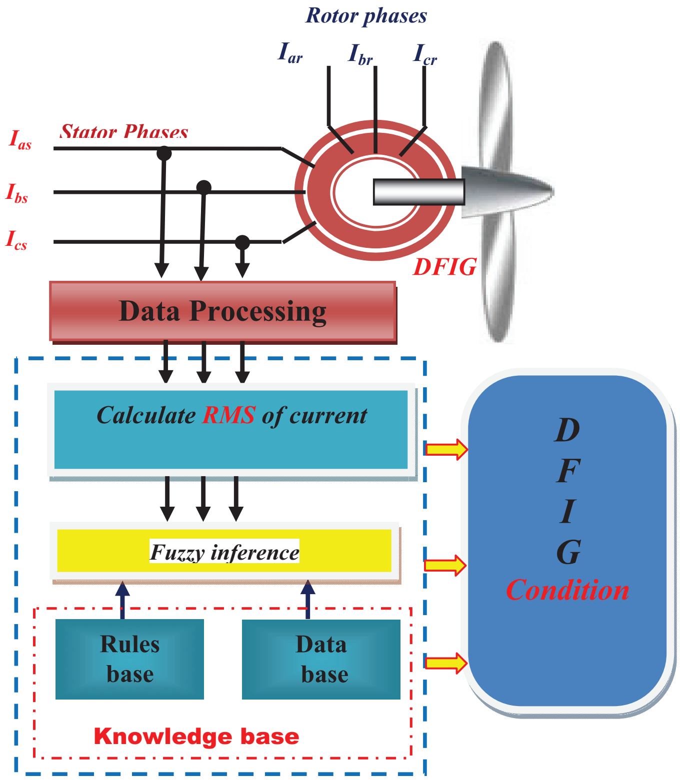


Fig.2. Monitoring system of DFIG state

4.2. Input-output variables of fuzzy system

The magnitudes of the stator currents (I_{as}, I_{bs} and I_{cs}) and the state of stator *CM,* are respectively selected as input and output variables of the fuzzy system. All these variables are defined by using the fuzzy set theory. Figure 3, shows that CM interprets the state of the stator as a linguistic variable, which could be T (CM) = {Healthy, Short-circuit, Critical Short-circuit, Open phase}.

Each limit in T (CM) is characterized by a fuzzy subset. The dialog system CM:

- {Healthy (H)}: interprets that the stator is healthy;
- {Short-circuit (SC)}: the stator present a short-circuit fault;
- {Critical Short-circuit (CSC)}: that the critical short-circuit fault;
- {Open phase (OP)}: interprets that the stator open phase fault.

The variables of input I_{as}, I_{bs} and I_{cs} are also interpreted as linguistic variables, with, T (Q) = {Zero (Z), Small (S), Medium (M), Big (B)} as it is shown in figure 4.

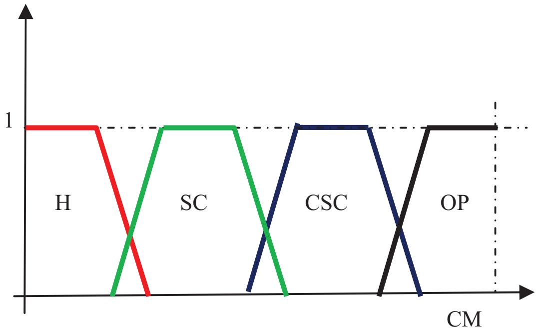


Fig.3. Membership functions for output variables

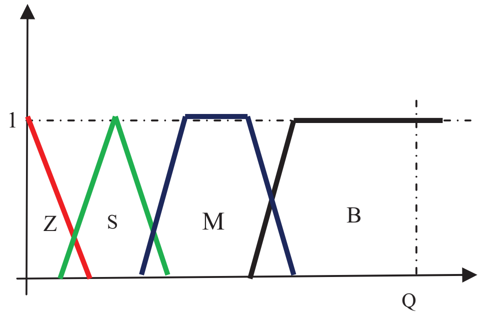


Fig.4. Membership functions for input variables

The fuzzy rules of the membership functions are built by the whole data observation (shown in Table 1). There is, however, 14 rules used starting from the membership functions for the input and the output. These rules are then defined, as the following:

Table 1. Fuzzy rules of the membership functions

Rules		I_{as}		I_{bs}		I_{sc}		***CM***
1	***If***	Z	***And***	🟥	***And***	🟥	***Then***	*OP*
2		🟥		Z		🟥		*OP*
3		🟥		🟥		Z		*OP*
4		B		🟥		🟥		*CSC*
5		🟥		B		🟥		*CSC*
6		🟥		🟥		B		*CSC*
7		S		S		S		H
8		M		M		M		H
9		S		S		M		SC
10		S		M		M		SC
11		M		S		M		SC
12		S		M		S		SC
13		M		S		S		SC
14		M		M		S		SC

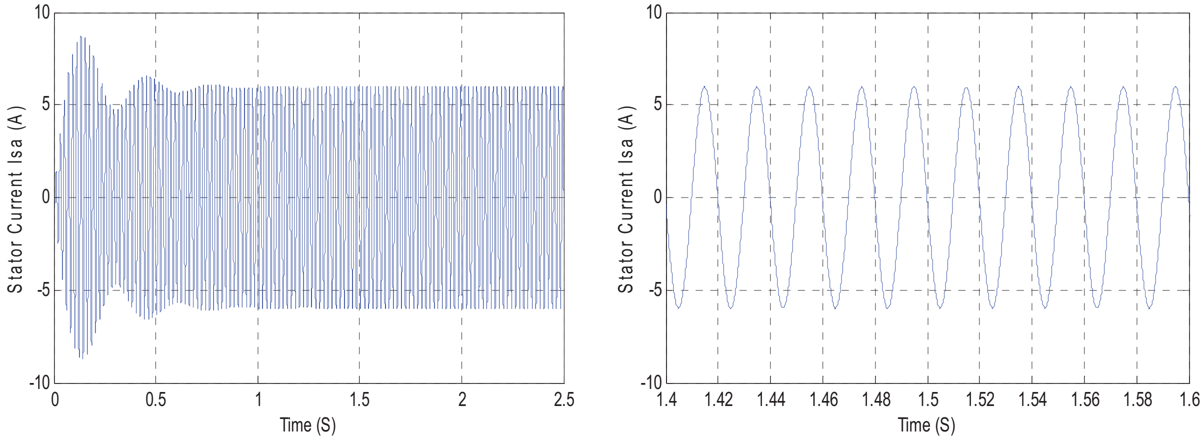
5. Simulations and interpretations

The figures 5.a and 5.b present respectively the current phase "a", the zoom part when the establishment is permanent. This latter shows clearly that the current is balanced (fig. 5 b).

The figure 5.c represents the output of the fuzzy value (the decision). This value is included in the interval CM = {Healthy [0 25]}, which corresponds to the limits of the healthy case. In addition, figure 4.d present the fuzzy inference diagram of the currents phases.

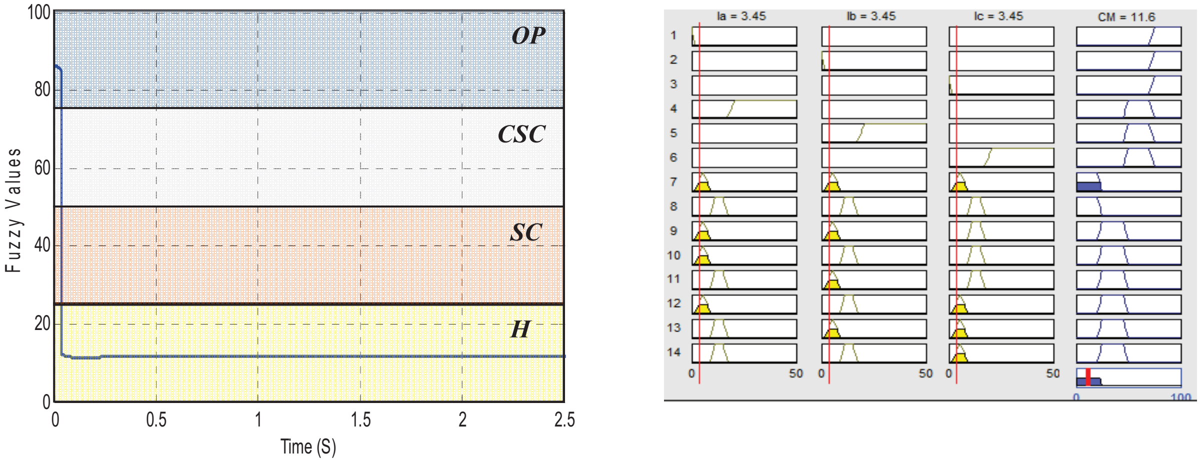
The continuation of the tests consist in analyzing the same sizes but when the generator presents tan open stator phase "a" (fig. 6), critical short-circuit faults with 35% of turns (fig. 7) and short-circuit faults with 15% turns of the phase "a" (fig. 8). These tests are basically the object of showing the possibility of detecting such a fault and also monitoring of the DFIG state and the severity of those faults. Indeed, it is noticed that the stator short-circuit or open phase faults cause an unbalanced of the generator currents. The increasing of the current magnitudes of the off the stator phases is clearly noticed, but with different rates, and this although the fault lies only in the level of the phase "a".

The figures 6.a-b, 7.a-b and 8.a-b are corresponding to tests of open stator phase, critical short-circuit and short-circuit, present increases in amplitudes proportional to the numbers (proportion) of the short-circuit stator turns or a cancellation of the current in the case of open stator phase. In addition the figures 6.c, 7.c and 8.c indicate values which correspond to those that indicate the presence of the fault. Indeed in the case of open phase stator the decision indicates CM = {Open phase [70 100]}, critical shorted-circuit stator with 35% of turns, the decision indicates CM = {Critical short-circuit [45 75]} and for 15% shorted-circuit turns, the decision indicates CM = {short-circuit [20 50]}. The figures 6.d, 7.d and 8.d present the fuzzy inference diagrams of the currents phases. Therefore, these tests validate that the approach is reliable and exploitable.



-a- Stator currents

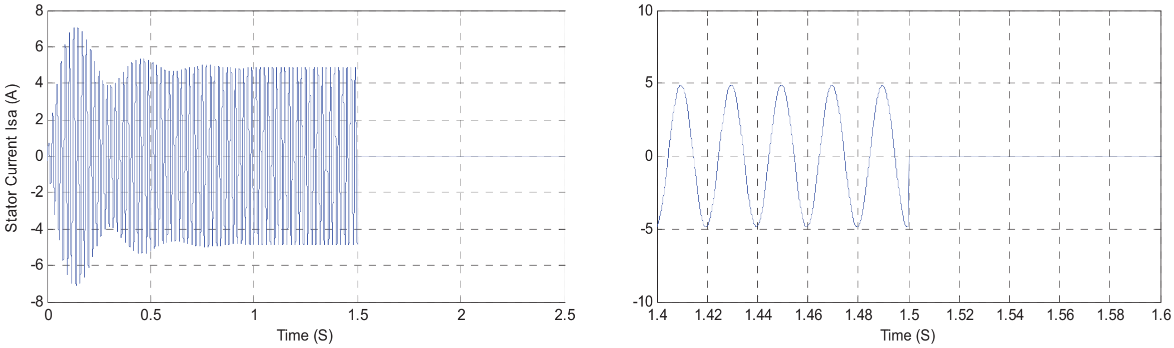
-b- Zoom of the stator currents



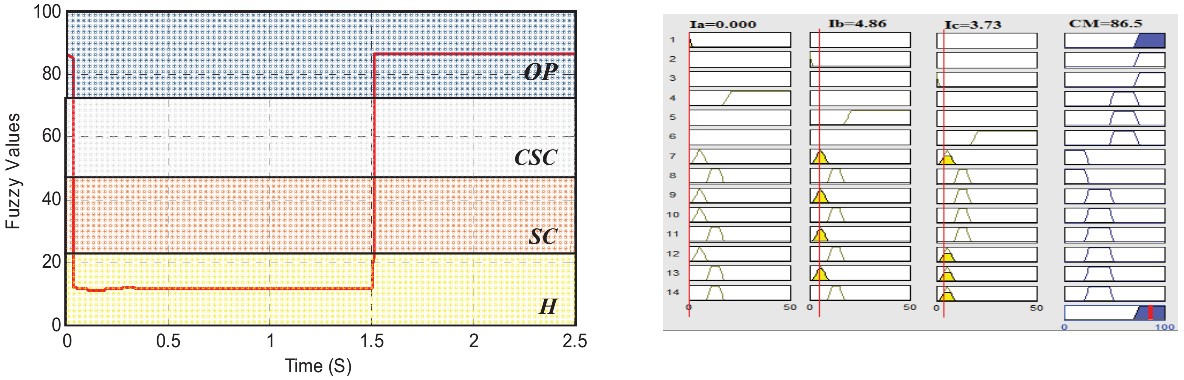
-c- Output fuzzy values

-d- Fuzzy inference diagram

Fig.5. Characteristics of the DFIG (healthy case)

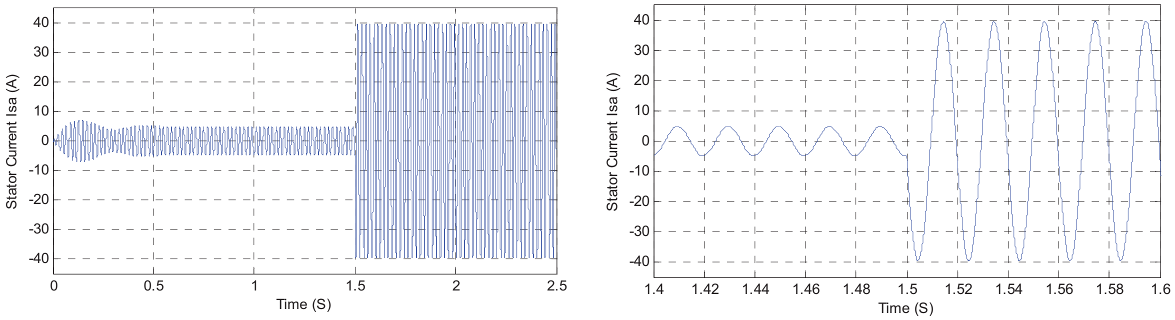


-a- Stator currents -b- Zoom of the stator currents

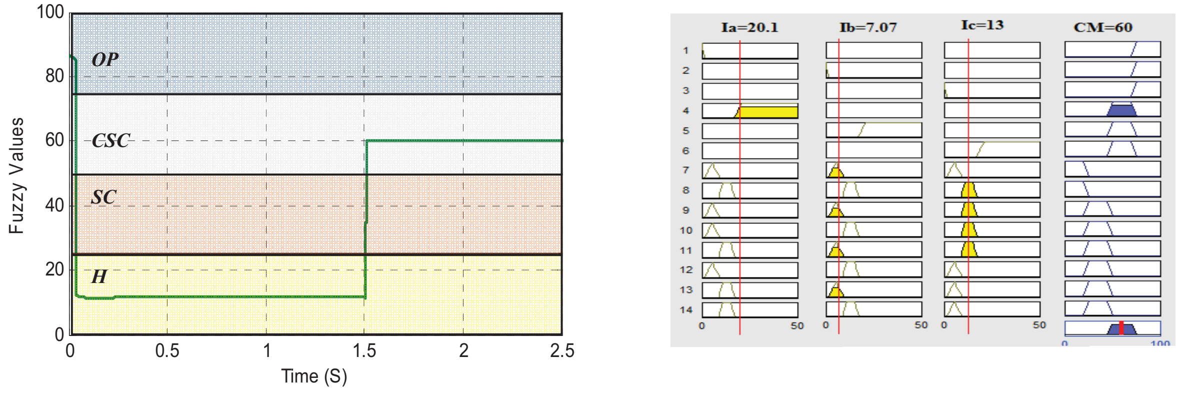


-c- Output fuzzy Values -d- Fuzzy inference diagram

Fig.6. Characteristics of the DFIG (Open phase case)



-a- Stator current -b- Zoom of the stator current

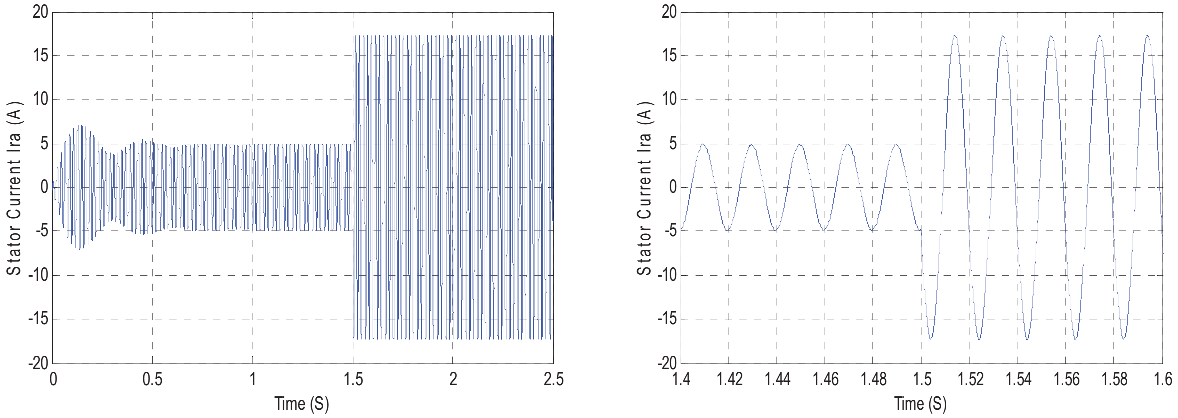


-c- Output fuzzy Values -d- Fuzzy inference diagram

Fig.7. Characteristics of the DFIG (critical short-circuit case)

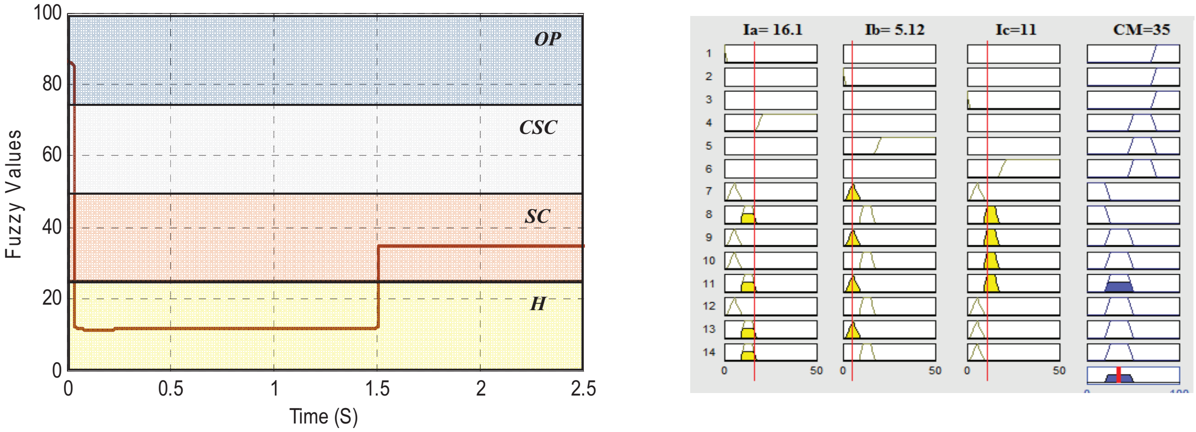
For prove that our approach of detection and monitoring of the doubly fed induction generator state gives satisfactory results even in the cases where the short-circuit fault or open phase stator is caused within the other phases (b and c) of the DFIG.

We tested our model in the case of a fault 35% of turn’s shorted-circuit and the open phase fault for the phase "b" and the phase "c".



-a- Stator current

-b- Zoom of the stator current



-c- Output fuzzy values

-d- Fuzzy inference diagram

Fig.8 Characteristics of the DFIG (short-circuit case)

6. Conclusion

In this paper, we presented the development of a doubly fed induction generator faults model then the simulation of these faults types. Only the first part of the mathematical model is represented then the simulation of healthy machine.

In the second part of this work we have assembled feasibility to monitoring and detecting the stator short-circuit fault between turns in a DFIG and open stator phases by supervising the current stator magnitudes using fuzzy logic techniques. In addition, this approach gives further information about the DFIG function condition to predict the fault severity.

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