Fuzzy monitoring of stator and rotor winding faults for DFIG used in wind energy conversion system

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Abstract: According to its high robustness, the use of doubly-fed induction generators in the wind energy conversion takes an important place in the world of production of electrical energy. This type of conversion became very attractive because of its manufacturing environments, low cost and operation with an easily available power supply. The increase interest in wind energy conversion has been accompanied by efforts to improve reliability, effective condition monitoring and better efficiency. In this work, a new technique is proposed for monitoring and detection of inter-turn short-circuit ITSC and open phase circuits in the stator or rotor windings of wind turbines based on doubly-fed induction generator. The principle of the suggested technique is based on the acquisition of the stator and the rotor currents of a doubly-fed induction generator with the aim to calculate the values of root mean square amplitude, in addition to the knowledge expressed in rules and membership function. This technique is verified using simulations performed via the model of doubly-fed induction generators built in MATLAB ® Simulink.

Keywords: doubly-fed induction generator; DFIG; monitoring; detection; short-circuit; open phase; fuzzy logic; root mean square; RMS.


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1 Introduction

The progress and utilisation of the wind energy conversion provoke the large use of the doubly-fed induction generator (DFIG), which is the main part of wind power generator. Mostly, stator and/or rotor windings short circuit, open stator and/or rotor circuit phase, rotor static, dynamic and mixed eccentricity, bearing, and multiplier, or the blades, are the major faults for wind turbines system. So it is very important for the protected function of generator to know all the fault characteristics of this machine type, especially winding inter-turn short circuit and open phase circuit defects (Li et al., 2013).

The inter-turn fault in stator or rotor windings is one of the most frequent faults in DFIG which is the principal
reason for a significant percentage that accounts for more than 30% of all DFIG failures. Inter-turn short circuit fault can be developed either due to total failure of insulation between turns generating direct inter-turns short-circuit or due to partial degradation of insulation between turns of stator or rotor windings resulting in incipient insulation failure (Sarkar et al., 2013; Wang et al., 2014).

The open stator or rotor circuit phases have several origins. This fault causes the cancellation of the current magnitude in the phase failing, the unbalancing of the current magnitude in other phases, and the significant undulation of torque. These consequences are less serious than a short-circuit fault since it does not have the problem of heating, which can breakdown the machine remainder, but it remains a fault which disturbs the generator function in the supply mode of electrical power energy (Millind et al., 2012; Ahmed et al., 2012; Chaturvedi et al., 2014).

The monitoring and detection of wind turbine faults was studied in many research works using various approaches because of its considerable interest in the field of production of electrical energy because the condition to obtain a safer system of production to ensure the continuity service in the conversion systems of wind power. Consequently, the systems of production of electrical energy must be equipped with reliable monitoring systems because possible breakdown can lead to considerable property damage (El Bouchikhi et al., 2012; Seshadrinath et al., 2014; Yanfeng et al., 2014; Entezami et al., 2012; Progovac et al., 2014). Indeed, the early detection of the failure makes it possible to minimise the turn-around time and consequently the downtime, to reduce the financial losses and the property damages to meet this requirement (Shashidhara and Raju, 2013; Schlechtingen and Ilmar, 2011).

Many research works reveal that stator or rotor currents and/or voltages signals are permanently modulated by fault monitoring in the DFIG. Different signal processing and signal analysis using mathematical techniques can identify faults in the DFIG (Shahata et al., 2013).

The main advantage of using electrical signals instead of any other types of signals is that the electrical signals can be directly measured and quantified (Aderiano et al., 2013; Siddiqui et al., 2014).

Several techniques for the monitoring and fault detection of inter-turn short circuit or open phase circuit in DFIG are established in the research works, such as the stator or rotor current signature analysing by fast Fourier transform (FFT), wavelet transformation transform (WT), extended transform Park’s (ETP), instantaneous power analyses (Ahadi et al., 2013; Ahamed et al., 2014).

The new techniques of control, estimation and monitoring of several electromechanical systems have widely used the artificial intelligence based on fuzzy logic using stator and the rotor currents of DFIG to calculate the values of root mean square (RMS) amplitude in addition to the knowledge expressed in rules and membership function (Bhardwaj and Agarawal, 2012; Mini et al., 2012; Du et al., 2015).

The proposed technique and the DFIG global model are simulated using software MATLAB®/Simulink and the obtained simulation results of healthy function, inter-turn short-circuit and open phase circuit faults are presented and interpreted.

2 Modelling of wind turbine

2.1 Modelling of mechanical system

2.1.1 Modelling of the turbine

The specific speed ($\lambda$) to characterise the aerodynamic performance of a wind turbine is expressed as follows:

$$\lambda = \frac{R\Omega}{V}$$  \hspace{1cm} (1)

With

- $\Omega$ angular velocity of the turbine rotation
- $R$ radius of the turbine
- $V$ speed of the wind.

The output mechanical power of wind turbine is given by the following equation (Berkakra and Ben Attous, 2012):

$$P_m = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V^3$$  \hspace{1cm} (2)

where the coefficient power ($C_p$) is given by the following relationship (Gaillaed, 2010):

$$C_p(\lambda, \beta) = C_1[\{C_2 a - b\} - C_3 \beta - C_4] e^{C_5 (a-b)} + C_6 \lambda$$  \hspace{1cm} (3)

With

- $a = \frac{1}{\lambda + 0.08\beta}\,$ and $b = \frac{0.035}{\beta^3 + 1}$
- $\beta$ pitch angle
- $C_1 = 0.5109, C_2 = 116, C_3 = 0.4, C_4 = 5, C_5 = 21,$
- $C_6 = 0.0068.$

2.1.2 Modelling of the gearbox

The gearbox adjusts the slow speed of the turbine ($\Omega_t$) to the generator fast speed ($\Omega_g$). It is mathematically presented by the following equations:

$$G = \frac{\Omega_g}{\Omega_t}$$  \hspace{1cm} (4)
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2.1.3 Modelling of the transmission shaft
The transmission shaft model proposed considering the total inertia \( J \) consists of turbine inertia \( J_t \) transferred to the generator rotor \( J_g \):

\[
G = \frac{J_t}{G^2} + J_g
\]  

Mechanical transmission modelling is:

\[
J \frac{\Omega_{\text{acc}}}{dt} = T_g - T_{\text{em}} - T_{\text{vis}}
\]  

where the viscous torque \( (T_{\text{vis}}) \) is proportional to the speed:

\[
T_{\text{vis}} = k_f \Omega_{\text{acc}}
\]

With

\[ k_f \] the friction coefficient.

2.2 Modelling of DFIG
Modelling must be adequate, so that the approach describes clearly the detection method (Toliyat and Sundaram, 2011).

The equations of the stator voltage and the rotor can be written in the following matrix form:

\[
\begin{bmatrix}
   v_{a} - v_{i_a} \\
   v_{b} - v_{i_b} \\
   v_{c} - v_{i_c}
\end{bmatrix}
= \begin{bmatrix}
   n & 0 & 0 \\
   0 & n & 0 \\
   0 & 0 & n
\end{bmatrix}
\begin{bmatrix}
   i_{a} \\
   i_{b} \\
   i_{c}
\end{bmatrix}
+ \frac{d}{dt}
\begin{bmatrix}
   \varphi_{a} \\
   \varphi_{b} \\
   \varphi_{c}
\end{bmatrix}
\]  

With

\[
v_{i_a} = -\frac{1}{3} \left( \frac{d}{dt} \varphi_{a} + \frac{d}{dt} \varphi_{b} + \frac{d}{dt} \varphi_{c} \right)
\]

where \( i = s \) is the index for the stator and \( i = r \) for the rotor.

Stator and rotor flows are expressed by:

\[
\begin{bmatrix}
   \varphi_{abc} \\
   \varphi_{abcr}
\end{bmatrix}
= \begin{bmatrix}
   L_{rs} & L_{sr} \\
   L_{sr} & L_{rr}
\end{bmatrix}
\begin{bmatrix}
   i_{abc} \\
   i_{abcr}
\end{bmatrix}
\]  

With

\[
L_{rs} = \frac{1}{2} L_{mi} - \frac{1}{2} L_{mi} - \frac{1}{2} L_{mi}
\]  

The matrix of mutual stator and rotor inductance is giving by:

\[
L_{sr} + L_{rs} = \begin{bmatrix}
   L_{m \cos A} & L_{m \cos B} & L_{m \cos C} \\
   L_{m \sin C} & L_{m \sin A} & L_{m \sin B} \\
   L_{m \sin B} & L_{m \sin C} & L_{m \sin A}
\end{bmatrix}
\]  

With

\[ A = \theta_r \]

\[
B = (\theta_r + 2\pi / 3); \\
C = (\theta_r - 2\pi / 3).
\]

where

\[
L_{mi} = \frac{\mu_0 r_l t}{g \left( \frac{N_s}{P} \right)} \]  

\[
L_{si} = \frac{\mu_0 r_l t}{g \left( \frac{N_r}{P} \right)} 
\]

electromagnetic torque equation:

\[
T_{\text{em}} = \frac{1}{2} \left[ L_s r_i \right] \begin{bmatrix}
   L_{sr} \\
   L_{rr}
\end{bmatrix}
\begin{bmatrix}
   i_s \\
   i_r
\end{bmatrix}
\]  

3 Model of the DFIG short-circuit fault
The voltage and flows equations of the wind generator in the presence of the short-circuit faults are (Soufi et al., 2013):

\[
\begin{bmatrix}
   v_{abc} \\
   v_{abcr}
\end{bmatrix}
= \begin{bmatrix}
   L_{sr} & L_{sr} & L_{sec} \\
   L_{sr} & L_{sr} & L_{sec}
\end{bmatrix}
\begin{bmatrix}
   i_{abc} \\
   i_{abcr}
\end{bmatrix}
+ \frac{d}{dt}
\begin{bmatrix}
   \varphi_{abc} \\
   \varphi_{abcr}
\end{bmatrix}
\]  

With

\[
\begin{bmatrix}
   \varphi_{abc} \\
   \varphi_{abcr}
\end{bmatrix}
= \begin{bmatrix}
   L_{sec} & L_{sec} & L_{sec} \\
   L_{sec} & L_{sec} & L_{sec}
\end{bmatrix}
\begin{bmatrix}
   i_{abc} \\
   i_{abcr}
\end{bmatrix}
\]

where

\[
L_{sec} \] mutual inductance between a stator phase and the short-circuit winding

\[
L_{sec} \] mutual inductance between a rotor phase and the short-circuit winding.
In the fault, we can write the various inductances of the winding of short circuit compared to the stator and rotor phases:

\[ L_{cci} = \eta_{cci}^2 (L_{m} + L_{0}) \]  

\[
\begin{bmatrix}
    L_{cci} \\
    L_{ccr} \\
    L_{ccs}
\end{bmatrix} = \begin{bmatrix}
    \frac{3}{2} \eta_{cci} L_{m} \cos(\theta_{cc}) \\
    \frac{3}{2} \eta_{cci} L_{m} \cos(\theta_{cc}) \\
    \frac{3}{2} \eta_{cci} L_{m} \cos(\theta_{cc})
\end{bmatrix} \begin{bmatrix}
    \sin(\theta_{cc}) \\
    \sin(\theta_{cc}) \\
    \sin(\theta_{cc})
\end{bmatrix} T_{23}
\]  

\[ L_{cci} = [L_{cci}] \]

\[
\begin{bmatrix}
    [L_{cci}] = \frac{3}{2} \eta_{cci} L_{m} P(-\theta) [T_{23}] \cos(\theta_{cc}) \\
    [L_{ccr}] = \frac{3}{2} \eta_{cci} L_{m} P(-\theta) [T_{23}] \cos(\theta_{cc}) \sin(\theta_{cc}) \\
    [L_{ccs}] = \frac{3}{2} \eta_{cci} L_{m} P(-\theta) [T_{23}] \cos(\theta_{cc}) \sin(\theta_{cc})
\end{bmatrix}
\]  

The relationship between the turn’s number in short-circuits and the number of healthy phase turns (\( \eta_{cci} \)) is defined by:

\[ \eta_{cci} = \frac{N_{cci}}{N_{ci}} \]  

After the transformation of the three-phase system into two-phase (\( \alpha, \beta \)) the voltage equations become:

\[
\begin{aligned}
U_{alpha} &= R_{c} \dot{\theta}_{fci} + \frac{d}{dt} \varphi_{alpha} \\
U_{beta} &= R_{c} \dot{\theta}_{fci} + \frac{d}{dt} \varphi_{beta} - \alpha P \left( \frac{\pi}{2} \right) \varphi_{beta} \\
0 &= \eta_{cci} R_{c} \dot{\theta}_{fci} + \frac{d}{dt} \varphi_{fci}
\end{aligned}
\]  

The flow equations are expressed by:

\[
\begin{aligned}
\varphi_{alpha} &= \varphi_{alpha} + \frac{d}{dt} \varphi_{alpha} = L_{alpha} \dot{\theta}_{fci} + L_{m} (\dot{\theta}_{fci} + \dot{\theta}_{fci} - \dot{\theta}_{fci}) \\
\varphi_{beta} &= \varphi_{beta} + \frac{d}{dt} \varphi_{beta} = L_{beta} \dot{\theta}_{fci} + L_{m} (\dot{\theta}_{fci} - \dot{\theta}_{fci} - \dot{\theta}_{fci}) \\
\varphi_{fci} &= \eta_{cci} Q(\theta_{cc}) \varphi_{fci}
\end{aligned}
\]  

With, the fault localisation matrix:

\[ Q(\theta_{cc}) = \begin{bmatrix}
    \cos^2(\theta_{cc}) & \cos(\theta_{cc}) \sin(\theta_{cc}) \\
    \cos(\theta_{cc}) \sin(\theta_{cc}) & \sin^2(\theta_{cc})
\end{bmatrix} \]  

\[ \tilde{\varphi}_{fci} = \sqrt{\frac{3}{2}} \eta_{cci} \dot{\theta}_{fci} \]  

\[ \tilde{\varphi}_{fci} = \sqrt{\frac{3}{2}} \eta_{cci} \varphi_{fci} \]

- \( \dot{\theta}_{fci} \) common magnetising flow
- \( \varphi_{alpha} \) stator leakage flows
- \( \varphi_{beta} \) rotor leakage flows.

The currents winding equation at fault is written:

\[ \dot{\varphi}_{fci} = \frac{2}{3} \eta_{cci} Q(\theta_{cc}) \frac{d}{dt} \varphi_{fci} \]  

The phases currents are the sum of the short-circuit currents and the currents consumed by the traditional model of Concordia. Thus, it becomes possible to express the winding equations at fault in the stator and rotor reference respectively can be written in the following form:

- If the short-circuit fault in the stator:

\[ \tilde{I}_{fci} = \frac{2}{3} \eta_{cci} Q(\theta_{cc}) \dot{I}_{fci} \]  

- If the short-circuit fault in the rotor:

\[ \tilde{I}_{fci} = \frac{2}{3} \eta_{cci} Q(\theta_{cc}) \dot{I}_{fci} \]

4 Monitoring of the DFIG-based fuzzy logic

4.1 Fuzzy monitoring system

The fuzzy system of detection is composed principally of detection where the RMS values are employed as input in the system fuzzy, and is based on the acquisition of the stator and rotor currents and the rules of knowledge base. The system of inference decides finally the stator and the rotor states (the faults type occurred with the stator and rotor windings) (Pandey and Choudhary, 2013; Mohanraj et al., 2012).

The diagram block of the approach suggested is shown in Figure 1.
4.2 Fuzzy system input and output variables

The amplitudes of the currents ($I_{as}$, $I_{bs}$, $I_{cs}$, $I_{ar}$, $I_{br}$, $I_{cr}$) and the stator and the rotor condition monitoring ($CM_s$ and $CM_r$) are the input and output variables of the fuzzy system.

The output fuzzy variables are defined as:

$CM_s$: condition monitoring of stator stat

$CM_r$: condition monitoring of rotor stat.

The input variables ($I_{as}$, $I_{bs}$, $I_{cs}$, $I_{ar}$, $I_{br}$, $I_{cr}$) are also interpreted as linguistic variables, with: $t(Q) = \{\text{very small (VS)}, \text{small (S)}, \text{medium (M)}, \text{large (L)}\}$, as it is showing in Figure 2.

Figure 2 Membership functions for input variables (see online version for colours)

The universe of discourse in Figure 3, shows that $CM_i$ values:

- {healthy ($H_i$)}: interprets that the stator or the rotor is healthy,
- {damaged ($D_i$)}: that a phase of the stator or rotor is in minor short-circuit faults,
- {seriously damaged ($SD_i$)}: the stator or the rotor has a critical short-circuit faults, and
- {open phase ($OP_i$)}: the open phase of stator or rotor.

Figure 3 Membership functions for output variables (see online version for colours)

Fuzzy rules membership functions for the input and the output. These rules are then defined in Table 1.

Table 1 Fuzzy rules member ship function (see online version for colours)

| Rules | $I_{as}$ and $I_{bs}$ and $I_{cs}$ | $I_{as}$ and $I_{bs}$ and $I_{cs}$ Then $CM_s$ |
|-------|---------------------------------|---------------------------------|---------------------|
| 01    | VS                             | OPs                            |                      |
| 02    | VS                             | OPs                            |                      |
| 03    | VS                             | OPs                            |                      |
| 04    | VS                             | OPs                            |                      |
| 05    | VS                             | OPs                            |                      |
| 06    | VS                             | OPs                            |                      |
| 07    | L                              | S                              | Ds                  |
| 08    | L                              | M                              | Ds                  |
| 09    | L                              | S                              | Hs                  |
| 10    | L                              | M                              | Hs                  |
| 11    | M                              | S                              | Ds                  |
| 12    | M                              | M                              | Ds                  |
| 13    | M                              | M                              | Dr                  |
| 14    | M                              | S                              | Dr                  |
| 15    | S                              | M                              | Dr                  |
| 16    | S                              | M                              | Dr                  |
| 17    | M                              | S                              | Dr                  |
| 18    | M                              | M                              | Dr                  |
| 19    | S                              | S                              | Dr                  |
| 20    | S                              | S                              | Dr                  |
| 21    | M                              | M                              | Dr                  |
| 22    | M                              | M                              | Dr                  |
| 23    | S                              | M                              | Dr                  |
| 24    | S                              | M                              | Dr                  |
| 25    | S                              | S                              | Dr                  |
| 26    | M                              | M                              | Dr                  |
| 27    | S                              | S                              | Dr                  |
| 28    | M                              | S                              | Dr                  |

Figure 4(c) are shows the fuzzy outputs values of rotor and stator decisions state, these values are included in the $CM_s$ intervals = \{healthy stator ($H_s$) [70 100]\} and $CM_r$ = \{healthy rotor ($H_r$) [70 100]\} which corresponds to the healthy case limits.

The continuation of the tests consisted of analysing the phase currents of the DFIG presents stator faults. Figures 5(a), 5(c) and 5(e) present respectively three phase stator currents ’$I_{as}$, $I_{bs}$, $I_{cs}$’ in the cases of open phase circuit in phase ’$I_{as}$’, damaged case of inter-turns stator short-circuit faults 15% and seriously damaged of critical inter-turns short-circuit with 35% of the turns of the phase ’$I_{as}$’. Corresponding to these tests an increase in the amplitude proportional to the number (percentage) of the inter-turns short-circuit stator or a cancellation of the current in the case of open stator phase can be observed.

5 Simulations and interpretations

The three phase stator currents ’$I_{as}$, $I_{bs}$ and $I_{cs}$’ with zoom and the three phase rotor current ’$I_{ar}$, $I_{br}$ and $I_{cr}$’ in the healthy case are respectively presented in Figure 4(a) and Figure 4(b). This latter shows clearly that the current is balanced.
Figure 4  Characteristics of the DFIG in healthy case, (a) stator currents (b) rotor currents (c) output fuzzy values (see online version for colours)

![Figure 4](image1.png)

Figure 5  Characteristics of DFIG in faults stator case, (a) stator currents (open phase) (b) output fuzzy values (OPs and Hr) (c) stator currents (seriously damaged in stator) (d) output fuzzy values (SDs and Hr) (e) stator currents (damaged in stator) (f) output fuzzy values (Ds and Hr) (see online version for colours)

![Figure 5](image2.png)

Figures 5(b), 5(d) and 5(f) respectively present the output fuzzy values (decisions) in the three stator faults type. These values are included in the CM intervals = {open phase stator (OPs) [0 25]}, CM = {seriously damaged in stator (SD) [20 50]}, and CM = {damaged in stator (SDs) [45 75]}, in this test the rotor remains always healthy CM = {healthy rotor (Gr) [70 100]}. These tests have as a principal objective to demonstrate the possibility of detect such a fault and of informing on its severity state, in the circuits stator and rotor.
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Figure 5 Characteristics of DFIG in faults stator case, (a) stator currents (open phase) (b) output fuzzy values (OPs and Hr) (c) stator currents (seriously damaged in stator) (d) output fuzzy values (SDs and Hr) (e) stator currents (damaged in stator) (f) output fuzzy values (Ds and Hr) (continued) (see online version for colours)

The model is tested for all the fault cases which show incontestably that the considered approach is valid and reliable.

Figure 6 Characteristics of DFIG in rotor faults case, (a) rotor currents (open phase) (b) Output fuzzy values (OPr and Hs) (c) rotor currents (seriously damaged in rotor) (d) output fuzzy values (SDr and Hs) (e) rotor currents (damaged in rotor) (f) output fuzzy values (Dr and Hs) (see online version for colours)

Figures 6(a) to 6(f) present respectively the similar studied faults but this time in the rotor. The approach of condition monitoring and detection of faults in the DFIG stator and/or rotor state give suitable results even for cases where the inter-turns short-circuit faults or the opening of the phases caused within the other stator or rotor phases (b and c) of the DFIG.
6 Conclusions

This paper presented the development of a healthy DFIG and a faulty one. Also, the simulation of the inter-turns short circuit defect with several percentages and the open phase circuit fault in stator or rotor of DFIG was carried out. The mathematical model was presented, then the simulation of the healthy generator. Furthermore, this work presented the possibility of the monitoring and detection of the inter-turns short-circuit in stator or rotor faults and the opening phase fault in the DFIG using fuzzy logic by supervising the amplitudes of the stator and rotor currents phases for calculate the RMS amplitude values.

In addition, this proposed technique is proved efficient in the progression of monitoring and detection of different severity levels of electrical faults in the winding rotor and stator of DFIG.

References


