

# Research on fault diagnosis of asymmetric stator winding for doubly-fed induction generators

Hongzhong Ma<sup>1</sup>, Yan Zhang<sup>1,3</sup>, Siyuan Li<sup>1</sup>, Zhuozhen Tang<sup>1</sup> and Zhengdong Zhang<sup>2</sup>

<sup>1</sup> Renewable Energy Generation Engineering, Hohai University, Nanjing, China;

<sup>2</sup> Maintenance Branch of Jiangsu Electric Power Company, Nanjing, China.

<sup>3</sup> 530167282@qq.com

**Abstract.** Magnetic field distribution, negative-sequence stator current, stator phase-angle difference between phase currents, and instantaneous rotor power were studied by theoretical analysis, modeling and simulation, experiment after stator winding fault in doubly-fed induction generators. Firstly, On the basis of analyzing the variation of magnetic field and stator current after stator winding inter-turn short circuit fault based on the finite element method, the variation of negative-sequence stator current and stator phase-angle difference between phase current were analyzed and studied. Grid model of doubly-fed induction generator was established in PSCAD, and through signal analysis it's found that the sensitivity and reliability of instantaneous rotor power spectrum are not only much better than those of current spectrum, voltage spectrum, but also better than those of negative-sequence component of stator current in slight fault diagnosis of stator winding. Finally, the experimental platform of stator winding fault for doubly-fed induction generator was built in the dynamic model laboratory of Hohai University, which further verified the reliability and superiority of instantaneous rotor power spectrum. So the synthetic diagnosis of stator winding fault for doubly-fed induction generator based on instantaneous rotor power with negative-sequence stator current and phase-angle difference between phase current is proposed.

## 1. Introduction

Wind power generation is highly increasing in the entire world [1]. The doubly-fed induction generation is the main type in wind power generation system [2-4]. Because of the bad operation environment and complex running states, the failure rate is high. Therefore, it's necessary to research on the fault diagnosis in the doubly-fed induction generator to find the early fault and repair it in time. It has great significance to improve the operation stability of wind farm and the reliability of power supply. It can also reduce the loss of motor's fault, reduce maintenance cost, and prolong the service life of the motor.

At present, the domestic and foreign scholars have done some research on fault diagnosis and monitoring of stator winding in Doubly-fed induction generator. In paper [5], the method that the stator winding fault in doubly-fed induction generations was monitored by using the rotor current spectrum was proposed, and the characteristic frequency that is not affected by the load factor was found. In paper [6], the method that the stator winding fault in doubly-fed induction generations was monitored by using the rotor current modulation signal was proposed. The methods proposed in paper [5], [6] don't require additional sensors and reduce the cost. But the expression of characteristic frequency contains slip  $s$ , so there is a high request on tracking and calculation accuracy of slip  $s$ ,



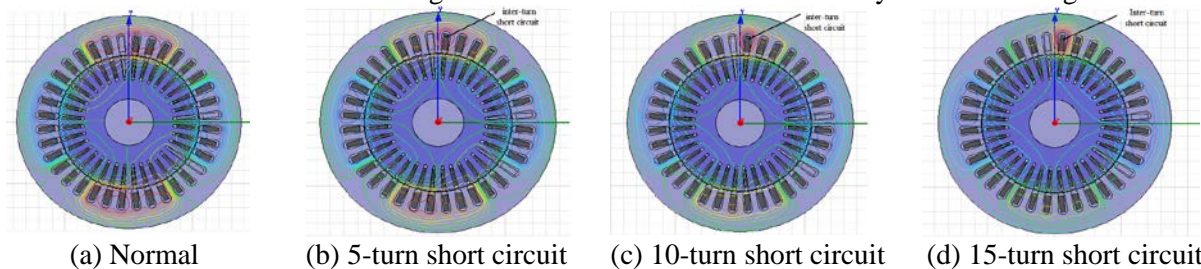
which increases the computation load. In this paper [7], the total error theory of linear dynamic system was applied to the fault diagnosis in doubly-fed induction generator, and the simulation analysis is carried out. Some scholars propose to monitor the stator winding fault by using the wavelet analysis [8], [9], axial flux [10], the radial stator and rotor vibration characteristics [11] and so on, but these characteristic quantities need to be further studied.

In the paper, the model of doubly-fed induction generator based on the finite element analysis was built firstly. It's found that stator current will appear additional negative-sequence current component after stator winding inter-turn short circuit fault. The variation of negative-sequence stator current and stator phase-angle difference between phase current are analyzed and studied. Grid model of doubly-fed induction generator was built in PSCAD, and it's found that the sensitivity and reliability of instantaneous rotor power spectrum are much better than those of current spectrum, voltage spectrum in slight fault diagnosis of stator winding. Finally, the experimental platform of stator winding fault was built in the dynamic simulation laboratory of Hohai University, which further verifies the reliability and superiority of the instantaneous rotor power spectrum. So the synthetic diagnosis of stator winding fault in doubly-fed induction generator based on the instantaneous rotor power with negative-sequence stator current and phase-angle difference between phase current is proposed.

## 2. Fault analysis of stator winding for doubly-fed induction generations

### 2.1. Analysis of the magnetic field variation after the stator winding inter-turn short circuit fault

The fault of doubly-fed induction generator was studied based on the change of magnetic field. From the point of view of the field, the finite element analysis software Ansoft 13 was used to carry out simulation research on stator winding inter-turn short circuit fault in doubly-fed induction generator.



**Figure 1.** Distribution of the magnetic field of stator winding in different states

The comparison in Figure 1 shows that the distribution of magnetic field is no longer even after the fault of stator winding of the motor and the distortion of magnetic field also increases with the aggravation of fault severity. This means that the change of magnetic flux is able to reflect the fault of stator winding inter-turn short circuit fault theoretically and can determine the fault location, but it's hard to achieve in the actual project. The variation of magnetic field can cause the variation of stator current, so the characteristic fault quantity of stator winding inter-turn short circuit can be found by analyzing the stator current.

### 2.2. Analysis of stator current variation after stator winding inter-turn short circuit

Assuming that a single turn coil of the generator carries current  $i_g$ , its magnetomotive force can be treated as the synthesis of two conductors' magnetomotive force, and the current of two conductors is same in size and opposite in direction. Via derivation, the Fourier Series expansion of magnetomotive force of single turn coil is:

$$F(\alpha) = \frac{2i_g}{\pi P} \sum_v \frac{1}{v} k_{yf} \cos(v\alpha) \quad (1)$$

Where,  $k_{yf} = \sin(v\alpha_y/2)$  is pitch factor of the coil;  $\alpha_y$  is electric space angle between two conductors; for short coil,  $v=1/p, 2/p, 3/p, \dots$ ; for Pitch coil,  $v=1/p, 2/p, 3/p, \dots$  and  $v \neq 2, 4, 6, \dots$

Assuming that the current  $i_f = \sqrt{2}I \cos(\omega t)$  is superimposed on a short circuit turn, according to equation (1), the magnetomotive force can be expressed as:

$$F(\alpha, t) = \frac{2\sqrt{2}I}{\pi P} \sum_v \frac{1}{v} k_{yf} \cos(\omega t) \cos(v\alpha) = \frac{\sqrt{2}I}{\pi P} \sum_v \frac{1}{v} k_{yf} \cos(\omega t \pm v\alpha) \quad (2)$$

Where,  $\omega=2\pi f_1$  is the power angle frequency.

Equation (2) shows that the magnetomotive force of additional current on short circuit turns is Pulsating, which can be decomposed into two circular rotating magnetomotive force with equal amplitude, the same speed and opposite direction. The circular rotating magnetomotive force in the positive rotation will induce positive-sequence current and the circular rotating magnetomotive force in the negative rotation will induce negative-sequence current. That is to say, after short circuit fault occurs, the negative-sequence stator current can be generated. So the negative-sequence stator current can be selected as characteristic quantity of stator winding inter-turn short circuit fault for doubly-fed induction generations, which can effectively diagnose the stator fault of generator.

### 2.3. Theoretical analysis of instantaneous power spectrum on rotor side

The instantaneous power of single phase on the rotor side for doubly-fed induction generator is defined as [12], [13].

$$p_a = u_a \times i_a \quad (3)$$

In the formula,  $u_a$  is the instantaneous value of the rotor phase voltage of doubly-fed induction generator. The phase voltage is directly measured in simulation, which is got through conversion of three-phase line voltage measured in experiment;  $i_a$  is instantaneous value of rotor phase-current of doubly-fed induction generator;  $p_a$  is instantaneous rotor single-phase power of doubly-fed induction generator.

The current and voltage on rotor side are both the ideal sine wave in normal conditions of doubly-fed induction generator, which can write as respectively (take phase A as an example):

$$\begin{cases} u_a = U_{ma} \cos \omega_1 t \\ i_a = I_{ma} \cos(\omega_1 t - \varphi) \end{cases} \quad (4)$$

In the formula,  $\omega_1$  is the angular frequency of fundamental voltage on rotor side, so it can be expressed as  $\omega_1=s\omega$ , and  $s$  is the slip,  $\omega$  is the angular frequency on stator side;  $U_{ma}$  is the amplitude of fundamental phase voltage;  $I_{ma}$  is the amplitude of fundamental phase current;  $\varphi$  is the phase angle that fundamental current backwards on fundamental voltage.

The instantaneous rotor power in phase A in normal conditions of doubly-fed induction generations can be obtained by equation (3) and equation (4):

$$p_a = \frac{1}{2} U_{ma} I_{ma} [\cos(2\omega_1 t - \varphi) + \cos \varphi] \quad (5)$$

Equation (5) shows that the frequency components of instantaneous rotor power in phase A are  $2f_1$  ( $f_1=sf$ ,  $f$  is the fundamental frequency on stator side) and a constant.

After stator winding fault of doubly-fed induction generator, the change of feature information on rotor side is more obvious than those on stator side, and the fault feature frequency component of electrical quantity on rotor side is  $[1+(n\pm v)(1-s)]f$  [14], where  $v$  is the Harmonic frequency. If  $v=1$ , this formula can be written as  $(2-s)f$ .

The instantaneous power on rotor side in phase A can be written as:

$$p_a = 1/2 U_{ma} I_{ma} [\cos(2\omega_1 t - \varphi) + \cos \varphi] + 1/2 U_{ma} I_{pa} [\cos(2\omega t - \varphi_{pa}) + \cos(2(\omega - \omega_1)t - \varphi_{pa})] \quad (6)$$

It can be seen in formula (6): After stator winding fault of doubly-fed induction generator, not only frequency components  $2f_1$  and a constant which is the same as those in normal are produced, but fault frequency components  $2f$  and  $2(1-s)f$  are produced. From the above analysis we can know that  $2f$ ,  $2(1-s)f$  can be chosen as fault features, but the slip  $s$  of doubly-fed induction generator is affected by wind speed which changes in real time, so the amplitude of frequency  $2f$  of instantaneous power spectrum on rotor side can be chosen as the fault feature frequency in order to avoid the calculation error of characteristic frequency caused by the tracking and calculating error of slip  $s$ .

### 3. Simulation and analysis of stator winding fault of double-fed induction generator

#### 3.1. The calculation and analysis of negative-sequence current

The generator model under different fault conditions is established in Ansoft, and the stator winding inter-turn short circuit fault of generator is simulated and calculated. Setting phase A into fault phase, the stator three-phase current in different conditions is obtained by changing the number of short circuit turns and the size of short circuit resistance of phase A in the model (the graph is omitted). The analysis showed that the three-phase current is not symmetric and the fault phase current increases with the increasing of fault severity level after the stator winding inter-turn short circuit fault. Phase-angle differences between phase current in different fault conditions are shown in table 1.

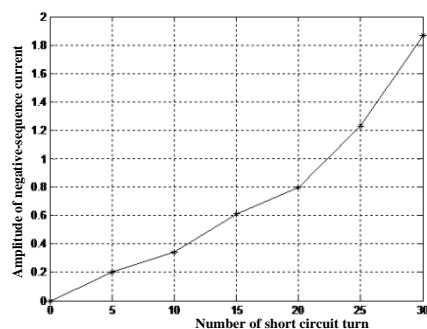
**Table 1.** Phase difference of stator current at different fault states of the stator winding

phase differences	normal	5-turn short circuit	10-turn short circuit	15-turn short circuit
phase AB	118.5°	121.1°	131.9°	135.1°
Phase AC	129.6°	125.1°	126.4°	129.6°
Phase BC	131.9°	126.4°	101.7°	95.4°

As can be seen in table 1:

The symmetry of phase differences among three-phase current is destroyed. The degree that phase difference between two non-faulty phases deviates from 120° is maximum (the non-faulty phases B and C in table 1), and the degree that phase difference deviates from 120° increases obviously with the increasing of fault severity level (in table 1, the phase difference between non-faulty phases B and C is 95.4° after 15-turn short circuit fault of phase A, which deviates from 120° is maximum).

The relationship between the amplitude of negative-sequence current and short circuit turns is shown in Figure 2. Figure 2 shows that after the stator winding inter-turn short circuit fault, stator current will appear negative-sequence component. It will increase with the increasing of severity level of inter-turn short circuit fault.



**Figure 2.** Relationship between negative sequence current and short-circuit turns

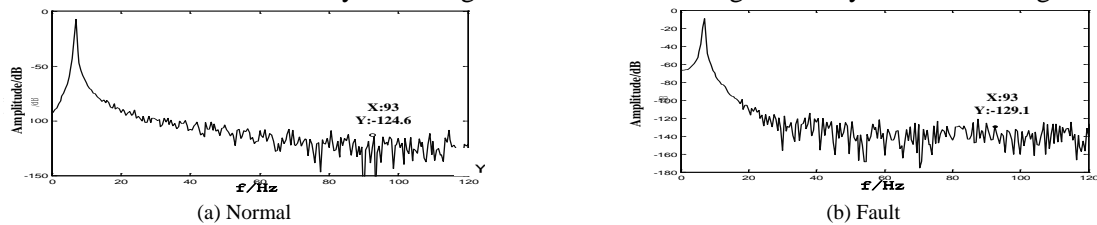
#### 3.2. The calculation and analysis of instantaneous power spectrum on rotor side

Firstly, fault model of doubly-fed induction generator is established in PSCAD. The model is simulated by the way that induction motor joins up frequency converter. The generator outlet is connected with the infinite system through transformer to realize the grid connected operation. Generator parameters are shown as follow:

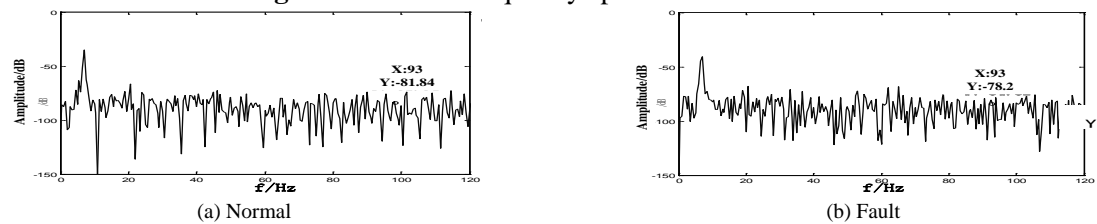
Rated capacity is 2MVA; rated line-voltage is 0.69kV; stator resistance is 0.0108pu; rotor resistance is 0.0121pu; mutual inductance is 3.362H; Leakage inductance of stator 0.102H; Leakage inductance of stator 0.11H; fundamental frequency 50Hz.

As can be seen from figure 3-5 that the amplitude of characteristic frequency changes 4.5dB and the change rate is 3.61% before and after fault in rotor current spectrum diagram; the amplitude of characteristic frequency changes 3.64dB and the change rate is 4.45% before and after fault in rotor voltage spectrum diagram; and the amplitude of characteristic frequency changes 51.9dB and the

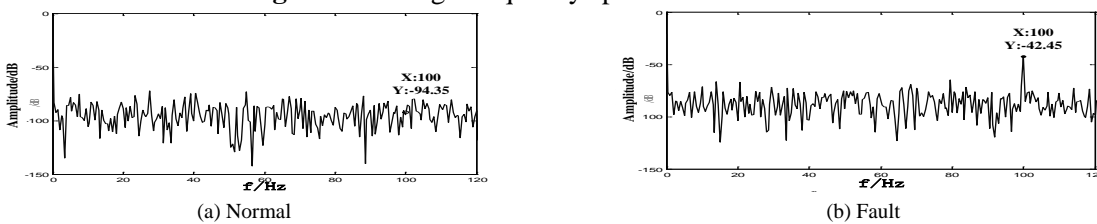
change rate is 55.01% before and after fault in instantaneous rotor power spectrum diagram. Obviously, when the slight fault of stator windings occurs, the changes in rotor current and voltage spectrum are not obvious, while the changes in instantaneous rotor power spectrum are very obvious, which are more conducive to early fault diagnosis of stator winding in doubly-fed induction generators.



**Figure 3.** Current frequency spectrum on rotor side.



**Figure 4.** Voltage frequency spectrum on rotor side.



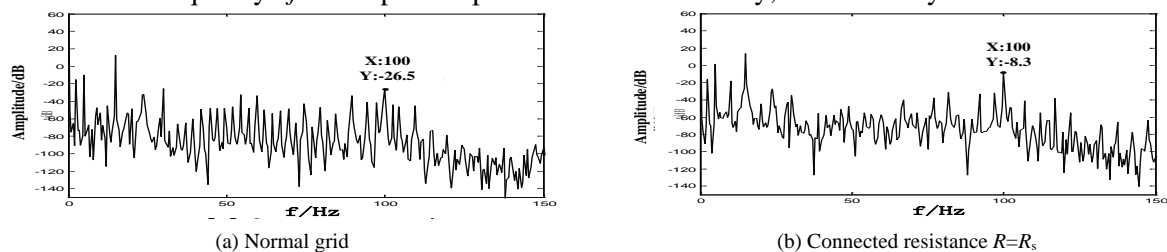
**Figure 5.** Instantaneous rotor power frequency spectrum.

#### 4. Construction of experimental platform and analysis of experimental results

The internal short circuit fault simulation of stator winding is difficult, but the asymmetric fault of stator windings can be achieved by a connected resistor  $R$  in phase A. This method that is simple and feasible doesn't need destructive experiment, and it is a common method to simulate the fault of stator winding.

The main parameters of motor YZR160M-4 are: Rated power of motor is 5.5kW; rated voltage of stator is 380V; rated current of stator is 12.5A; rated voltage of rotor is 18V; rated current of rotor is 20A; rated speed is 1445rpm.

The figure 6 shows changes of power spectrum in conditions of normal grid and the stator winding connected resistance  $R=R_s$  at speed 1425rpm. The amplitude of characteristic frequency  $2f$  changes 18.2dB and the change rate is 66.7% before and after fault. It can be seen that the amplitude of characteristic frequency  $2f$  of the power spectrum varies obviously, which is very sensitive to the fault.



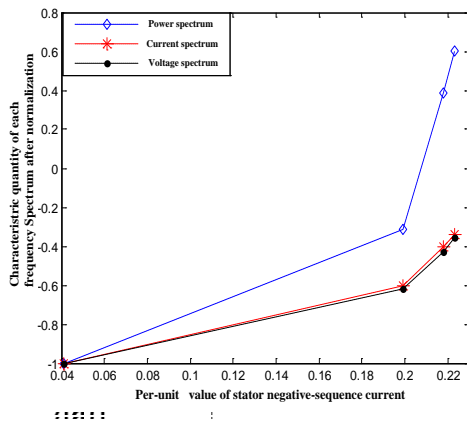
**Figure 6.** Instantaneous rotor power spectrum.

Table 2 shows negative-sequence stator current ratio and the characteristic frequency amplitudes of current spectrum, voltage spectrum and power spectrum on rotor side at speed 1425rpm. From the table 2, It can be seen that when stator winding is connected by resistance  $R=R_s$  ( $R_s$  is the stator

resistance) Per-unit value of negative-sequence current is 0.199; the characteristic frequency amplitude of current spectrum changes 35.7dB and the change rate is 39.90%; the characteristic frequency amplitude of voltage spectrum changes 36.9dB and the change rate is 38.20%; while the characteristic frequency amplitude of power spectrum changes 18.2dB and the change rate is 68.68%. So the amplitudes of current spectrum and voltage spectrum change more than amplitudes of power spectrum, but the change rate of power spectrum is much greater. Figure 7 is the frequency spectrum contrast diagram of current, voltage, power spectrum on rotor side after normalization (the absolute of Amplitude divided by initial amplitude).

**Table 2.** Amplitudes of characteristic frequency on rotor side at speed 1425rpm.

Fault state	normal	$R=R_s$	$R=3*R_s$	$R=5*R_s$
Negative-sequence stator current ratio $I_2/I_1$	0.041	0.199	0.218	0.223
Amplitude change of current spectrum on rotor side(dB)	-89.5	-53.8	-36.2	-30.3
Amplitude change of voltage spectrum on rotor side(dB)	-96.6	-59.7	-41.5	-34.3
Amplitude change of power spectrum on rotor side(dB)	-26.5	-8.3	10.3	15.9



**Figure 7.** The frequency spectrum contrast diagram after normalization.

It can be seen that from figure 7 that the amplitude change of the power spectrum  $2f$  is the most obvious with the increasing of negative-sequence current Per-unit value (three-phase unbalance). It indicates that the instantaneous power spectrum is more sensitive than current and voltage spectrum on rotor side in fault diagnosis of stator winding.

## 5. Conclusions

This paper started from magnetic field changes of the stator winding inter-turn short circuit. Then the fault features, negative-sequence stator current, stator phase-angle difference between phase current and instantaneous rotor power are proposed. The following conclusion can be achieved:

(1) After inter-turn short circuit fault of stator winding, the negative-sequence stator current increases and the degree that phase difference between non fault phases deviates from  $120^\circ$  increases with the increasing of the fault severity level.

(2) The characteristic frequency  $2f$  of rotor power spectrum is not affected by the slight change of slip  $s$ , which has low request on tracking accuracy and reduces the computation load.

(3) The simulation and experiment show that when the stator winding is in the state of slight fault, the characteristic frequency amplitude changes of current and voltage spectrum on rotor side are not obvious; when the stator winding is in the state of serious fault, the characteristic frequency amplitude changes of current and voltage spectrum on rotor side are obvious, but the characteristic frequency amplitude changes of power spectrum are more obvious.

In summary, the amplitudes of characteristic frequency  $2f$  of rotor power spectrum with the negative-sequence current and phase angle differences between phase-current are chosen as characteristic quantity of stator winding fault, whose reliability and sensitivity can be guaranteed. In

the actual condition monitoring of doubly-fed induction generator, set the amplitude of characteristic frequency  $2f$  of rotor power spectrum, negative-sequence current and phase-angle differences between phase current to a certain threshold alarm mechanism to realize the digital control.

### Acknowledgment

The project is supported by Chinese National Natural Science Foundation under Grant 51577050.

### References

- [1] Alireza J and Roshanfekar R 2016 Wavelet-based index to discriminate between minor inter-turn short-circuit and resistive asymmetrical faults in stator windings of doubly-fed induction generators: a simulation study *IET Generation Transmission & Distribution* **10** 374
- [2] WANG H.S., ZHANG W. and HU J. B. 2010 A Control Strategy for Doubly-fed Induction Generator Wind Turbines Under Asymmetrical Grid Voltage Conditions Caused by Faults *Automation of Electric Power Systems* **34** 97
- [3] CAO J., WANG H. F. and QIU J. J. 2009 Frequency control strategy of variable speed constant frequency doubly-fed induction generator wind turbines *Automation of Electric Power Systems* **33** 78
- [4] DING S.Y., SUN Z. Q. and JIANG N. 2011 Numerical simulation of rheological properties inside large doubly-fed wind generator *Electric Machines and Control* **15** 28
- [5] Shah D, Nandi S and Neti P 2007 Stator Inter-turn Fault Detection of Doubly-fed Induction Generators Using Rotor Current and Search Coil Voltage Signature Analysis *IEEE Transactions on Industry Applications Industry Applications Conference* (New Orleans, LA, USA) 1948
- [6] Stefani A, Yazidi A and Rossi C 2008 Doubly-fed induction machines diagnosis based on signature analysis of rotor modulating signals *IEEE Transactions on Industry Application* **44** 1711
- [7] Bennouna O, Heraud N and Rodriguez M 2006 Gross Error Detection Applied to a Wind Turbine *IMACS Multi-conference on "Computational Engineering in Systems Applications"* (Beijing, China) 843
- [8] Watson S. J, Xiang B.J and Wenxiang Yang 2010 Condition monitoring of the power output of wind turbine generators using wavelets *IEEE Transactions on Industry Application* **25** 715
- [9] Al-Ahmar E, Benbouzid M E H and Amirat Y 2008 DFIG-based wind turbine fault diagnosis using a specific discrete wavelet transform *IEEE International Conference* (Vilamoura, Portugal) 1736
- [10] Penman J, Sedding H G and Lloyd B A 1994 Detection and location of interturn short circuits in the stator windings of operating motors *IEEE transactions on Energy conversion* **9** 652
- [11] WAN S.T, LI H.M. and XU Z. F. 2004 Analysis of generator vibration characteristic on stator winding inter-turn short circuit fault *Proceedings of the CSEE* **24** 161
- [12] Hachemi E Benbouzid MA 2000 review of induction motors signature analysis as a medium for faults detection *IEEE Transactions on Industrial Electronics* **47** 984
- [13] El Hachemi Benbouzid M 2000 A review of induction motors signature analysis as a medium for faults detection *IEEE Transactions on Industrial Electronics* **47** 984
- [14] LI junqing, WANG Dong, HE Long 2013 Steady-state analysis on inter-turn short circuit fault of stator windings in doubly-fed induction generators *Automation of Electric Power Systems* **37** 103