Diagnosis of Inter-Turn Short Circuit and Rotor Eccentricity for PMSG Used in Wave Energy Conversion

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***Abstract*—In this paper, the stator winding inter-turn short circuit and the rotor eccentricity hybrid fault of permanent magnet synchronous generators (PMSG) used in wave energy conversion is analyzed by using a coupled field-circuit method with the saturation being taken into account. The harmonic current and the vibration spectrum were used in order to investigate this kind of fault. The diagnosis system was tested over a PMSG with novel rotor suitable for middle-power wave power generation applications. The online electrical and vibration characteristics detection test was performed by using three current transformers, a digital signal processor (DSP) board, and a personal computer, including an accelerometer sensor, a vibration amplifier, and a DL750 ScopeCorder with a configurable control circuit for switch open faults of generator-side rectifier and grid-side inverter involved. Simulation and experimental results have shown that the sideband frequency currents at 25 Hz and 75 Hz, and the 17th and 19th order components of terminal currents can be used as fault detection criteria. Furthermore, the vibration spectrum can aid the method, being an auxiliary fault detection index.**

Keywords—Permanent magnet synchronous generator; inter-turn short circuit fault; dynamic eccentricity; vibration

I. Introduction

Due to the overuse of fossil fuels, mankind is facing with the dual pressures of fossil energy crisis and environmental degradation. There is an urgent need to develop renewable clean energy sources. In the meantime, ocean wave energy has gained considerable attention as a type of enduring, abundant, and predictable renewable energy source and many different kinds of devices for wave energy conversion have been developed. Generator is obviously one of the key components of wave energy conversion system [1, 2]. When compared with induction generator, doubly-fed induction generator, synchronous generator, permanent magnetic synchronous generator (PMSG) seems to be the most widely used kind generator in wave energy conversion system. This generator's outstanding advantages are its simple structure, high efficiency, small size, good environmental suitability, better power grid connection and easy control ability [3-6]. Further, online monitoring of PMSGs used in wave energy conversion plays an vital role on the system operation. Hence, investigations on fault detection of PMSG is also important for the reliability improvement of wave power generation.

To date, there have been many investigations on the modeling and detection of stator windings inter-turn short circuit fault in the electrical machines including the PMSG. A technique for partitioning of the winding, proposed in [7], was applied to internal fault analysis and determining the corresponding winding inductances. A method for simulating internal faults in a synchronous generator with the direct phase quantities was fully described in [8, 9].

In order to improve the numerical efficiency and accuracy of the phase domain model, the voltage-behind-reactance representation technique and the modified winding function theory were developed in [10] and [11] respectively, while the internal faults were taken into account. The well-known multi-loop analysis method was proposed in [12], and has been widely used in [13-17]. Another method was put forward to analyze the transient behaviors of synchronous generator [18], which was declared to able to treat any conceivable faults in the machine.

Among these modeling approaches of stator windings inter-turn short circuit faults in synchronous generator, the coupled field-circuit method is one of the most promising one, since it can solve nonlinear problems, such as saturation, hysteresis and eddy losses. The quantities that could be used to monitor and diagnose the stator windings inter-turn short circuit faults in generator including currents, voltages, torque pulsations, temperature increase, shaft vibrations, air-gap flux, and speed ripples [19]. The most popular approaches used for the stator inter-turn fault detection in electrical machines are: the symmetrical component method [20], the park's vector approach [21], the FFT spectrum analysis [22, 23], the wavelet transform method [24, 25], and other intelligent fault detection techniques [26].

A coupled field-circuit method by taking into account the saturation is proposed in [27] to design PMSM, which is used in wind power generation. In this paper, we will still use this method to model the PMSM used in wave power generation, with the wave input simulated by an all-electrical-analogue equivalent method, i.e. the "force-voltage" and "velocity-current" mapping relationships [28]. The generator vibration characteristic caused by stator winding inter-turn short circuit fault has been analyzed without taking the eccentricity into

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account in [29]. It has pointed out that the vibration signal could be the symptom of stator winding faults, rotor eccentricity and other faults, as well as the electrical parameters, though less experiment vibration data has been provided yet. As reported in [30], the Extended Park's Vector Approach (EPVA) is able to detect and locate the stator winding inter-turn faults in three-phase induction motors. This method was successfully applied in the diagnosis of stator winding faults, rotor cage faults, unbalanced supply voltage, and mechanical load misalignments [31-34].

Since the rotor eccentricities fault in electrical machines usually occurs with other faults [35-43], this paper aims to study the hybrid fault, namely the stator winding inter-turn short circuit fault and the rotor eccentricity fault through online electrical and vibration detection test. Harmonic currents analysis is performed to enhance the detection accuracy. Information about the vibration characteristic of the PMSG are evaluated as the additional fault characteristics for this hybrid fault so that a comprehensive fault detection for the generator is achieved. This paper is organized as follows. Section II presents the finite element (FE) model for PMSG. The common methods employed to model and detect the inter-turn short circuit and eccentricity fault are described. The hybrid fault is analyzed by the coupled field-circuit method and FFT technique. In section III, related experimental results are provided to verify the aforementioned fault diagnosis approaches, including the vibration test. Finally, conclusions are drawn in section IV.

II. Modeling of Inter-Turn Short Circuit and Eccentricity with Couple Field-Circuit

A. Finite Element Model (FEM)

Table I shows the performance comparison of different generators used in wave energy conversion system. It can be found that the PMSG maybe the most suitable one.

TABLE I
PERFORMANCE CHARACTERS OF GENERATOR WITH DIFFERENT TYPES

Generator type	Environmental suitability	Efficiency	Cost	Power grid connection
SCIG	Good	Low	Low	Bad
DFIG	Bad	Average	Average	Worse
SG	Bad	High	High	Good
PMSG	**Good**	**Higher**	**High**	**Good**
PMLG	Good	High	High	Good

Taking the saturation and other nonlinear effects into account, the couple field-circuit method [18, 27] is used to model the stator winding inter-turn short circuit fault and air-gap eccentricity in PMSGs.

Neglecting the displacement current and the magnetic hysteresis effect, the electromagnetic governing equation for a PMSG can be represented as

$$\frac{\partial}{\partial \boldsymbol{x}}\left(\boldsymbol{v}\frac{\partial \boldsymbol{A}_z}{\partial \boldsymbol{x}}\right)+\frac{\partial}{\partial \boldsymbol{y}}\left(\boldsymbol{v}\frac{\partial \boldsymbol{A}_z}{\partial \boldsymbol{y}}\right)=-\boldsymbol{J}_z+\boldsymbol{\sigma}\frac{\partial \boldsymbol{A}_z}{\partial \boldsymbol{t}} \qquad (1)$$

where $\boldsymbol{A}_z$ is the magnetic vector potential, $\boldsymbol{J}_z$ is the current density, and v and σ are the material reluctivity and conductivity respectively. Using Galerkin discretization method, equation (1) can be rewritten as

$$\boldsymbol{T}\cdot \mathrm{p}\boldsymbol{A}+\boldsymbol{K}\cdot\boldsymbol{A}=\boldsymbol{C_b}\cdot\boldsymbol{I_b} \qquad (2)$$

where $\boldsymbol{A}$ is the magnetic vector potential to be solved; $\boldsymbol{I}_b$ is a Z-dimension current vector, in which Z represents the number of equivalent windings; p is the differential operator; $\boldsymbol{T}$ is the eddy current coefficient matrix; $\boldsymbol{K}$ is the element stiffness matrix; and $\boldsymbol{C}_b$ is the node incidence matrix for $\boldsymbol{I}_b$.

B. Multi-loop Model with Inter-turn Short Circuit Fault

Fig. 1 shows a typical multi-loop model diagram of the stator winding for the electrical machine with an inter-turn short circuit fault in different branch at phase A. In this condition, there are two additional branches has been added in the model. Using this model (N_s stator loops) with N_d rotor damping loops, the voltage equation of all the N loops ($N=N_s+N_d$) can be represented as

$$\boldsymbol{U'}=\mathrm{p}\boldsymbol{\Psi'}+\boldsymbol{R'}\cdot\boldsymbol{I'} \qquad (3)$$

where $\boldsymbol{R'}$ is a $N\times N$ matrix, $\boldsymbol{U'}$, $\boldsymbol{\Psi'}$ and $\boldsymbol{I'}$ represents the $N\times1$ column vector of voltage, flux and current for each loop respectively.

The loop current $\boldsymbol{I'}$ and $\boldsymbol{I}_b$ will satisfy

$$\boldsymbol{I_b}=\boldsymbol{G}\cdot\boldsymbol{I'} \qquad (4)$$

where $\boldsymbol{G}$ is the incidence matrix between the branch and loop circuits.

Notice that the flux $\boldsymbol{\Psi'}$ contains two parts: the ending flux linkage $\boldsymbol{\Psi}'_L$ and the remainder linkage $\boldsymbol{\Psi}'_M$. The latter one is related to the saturation, and can be calculated from the finite element model.

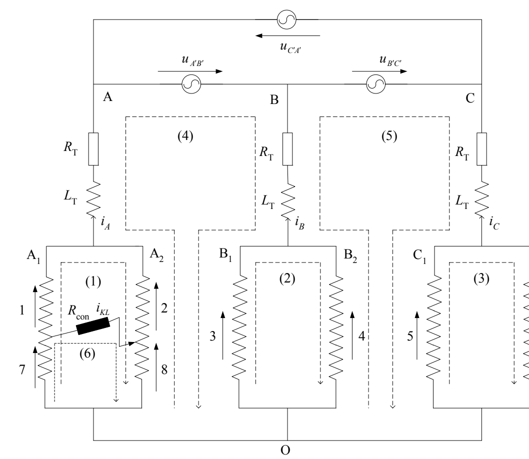


Fig. 1. Multi-loop model of stator winding.

Further, the rotor motion equation is

$$J_m \frac{d\omega}{dt} = T_m - T_e \tag{5}$$

where T_e is electromagnetic torque, T_m is the input torque of generator, J_m is the inertia of PMSG, ω is the rotor angular speed.

Then combine equation (2), (4) and (5), the multi-loop model of the PMSG with inter-turn short circuit fault can be modelled.

C. Eccentricity Fault

Static eccentricity (SE) and dynamic eccentricity (DE) are two typical kinds of eccentricity in electrical machines. These two eccentricities can all result in a nonuniform air gap between the stator and the PM rotor, which is shown in Fig. 2. In Fig. 2, O_s is the symmetry center of stator, O_r is the rotor symmetry axis, and O_w is the rotor rotation center. In Fig. 2, it can be seen that the whirling angular velocity is the same as the mechanical angular velocity of the rotor under DE.

The degree of DE is defined as

$$e = \frac{\Delta e}{g} \times 100\% \tag{6}$$

where g is the average air-gap length, and $\Delta e = |O_r O_w|$ is the dynamic eccentricity vector in PMSG.

Here, the static and dynamic eccentricity is realized by placing the rotor in a new position with mesh regeneration in the FEM. Fig. 3 shows the corresponding FEM for the PM generator with 60 stator slots and a 4-poles rotor which is used in this paper. The new rotor is designed by the non-uniform air gap method as shown in Fig. 3, in order to enhance the output torque of generator. This can improve the adaptability of the PMSG in wave energy conversion.

D. Hybrid Fault Analysis

It has been pointed out in [27] and [42] that the DE fault can be diagnosed by using a novel pattern frequency, calculated as

$$f_{eccentricity} = \left[1 \pm \left(\frac{2k-1}{P}\right)\right] f_s \tag{7}$$

where P is the number of pole pairs, k is an integer number 1, 2, 3…, and f_s is the supply frequency.

As same as [27]. Thus, the sideband frequency currents at 25 Hz and 75 Hz as indicated in (7), and the 17th and 19th order harmonic currents are chosen to be the fault indicators for the inter-turn short circuit and DE hybrid fault.

Combined the FE model with the multi-loop method, the 17th and 19th order harmonic currents spectrum under inter-turn short circuit and dynamic eccentricity hybrid fault are shown as Fig. 4. In this condition, the inter-turn short circuit fault occurs between the stator winding taps A_{11} and N according to the parameters of the experimental generator which will be discussed in Section III. Fig. 5 shows the corresponding results of the sideband frequency harmonic currents at 25 Hz and 75 Hz with the same hybrid fault.

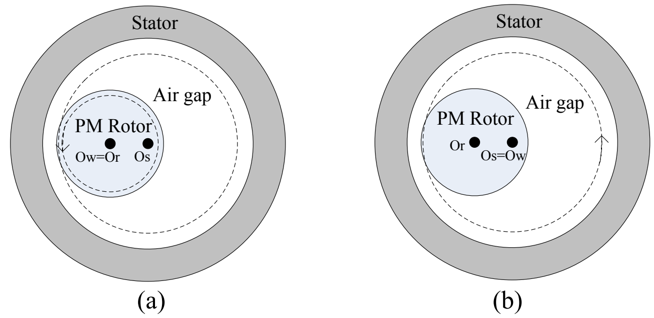


Fig. 2. Schematic diagram of eccentricity for PMSG: (a) static eccentricity; (b) dynamic eccentricity.

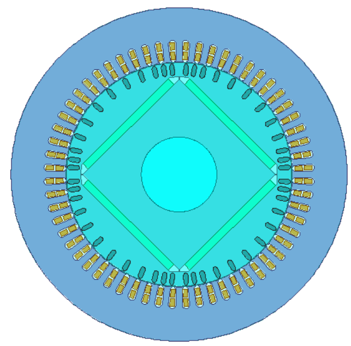
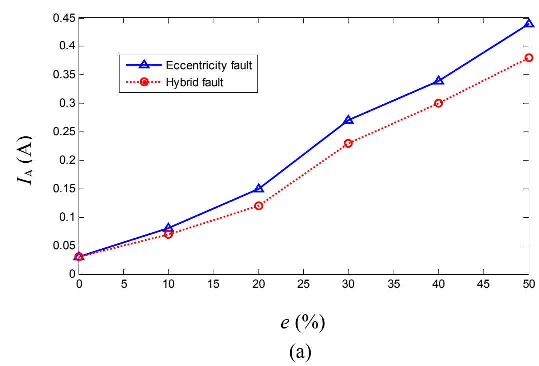


Fig. 3. Finite element model with new rotor punching.



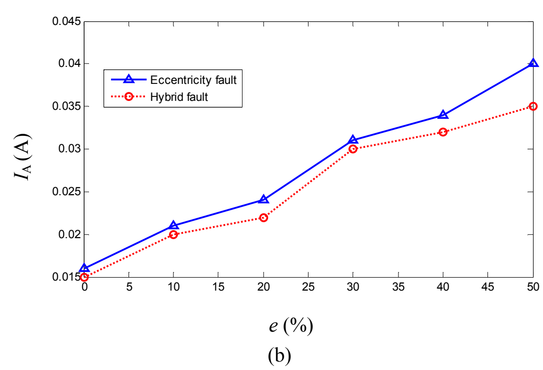


Fig. 4. The terminal harmonic currents under eccentricity: (a) the 17th order; (b) the 19th order.

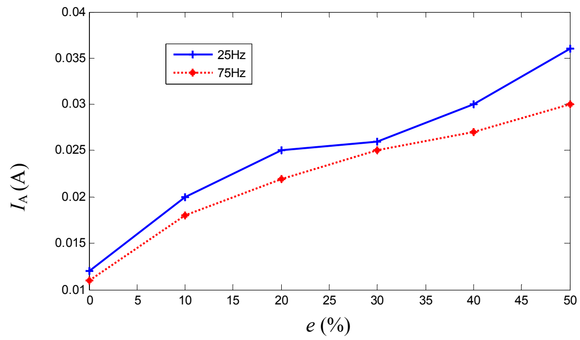


Fig. 5. Terminal sideband frequency harmonic currents under eccentricity.

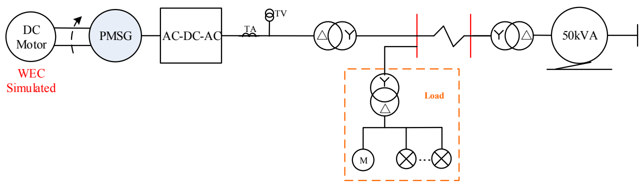


Fig. 6. Experiment set-up.

From Fig. 4, we can see that the amplitude of the 17th and 19th harmonics (phase A) decreases when the inter-turn fault occurs. Notice that the 17th harmonic is bigger than the 19th one. The 17th and 19th harmonics increase when increasing the percentage of dynamic eccentricity. In Fig. 5, the sideband frequency harmonic currents at 25 Hz and 75 Hz also increase with the DE severity. In addition, the 25 Hz harmonic current is bigger than the 75 Hz component. Results in Fig. 4 and Fig. 5 also show that the harmonics of the generator have been reduced with the optimal design of the stator and rotor compared to those in [27].

III. Experimental Results

A. Experimental Model and Generator Parameters

In order to verify the proposed method, an experiment set-up has been built and tested as shown in Fig. 6. A 7.5 kVA permanent magnet synchronous generator was used, whose stator winding arrangement is shown in Fig. 7. In Fig. 7, the eight taps for short-circuit experiment of the generator are also presented. A separately excited DC motor was utilized to drive the PMSG in the lab experiments. Finally, a back-to-back converter was applied to transfer the electrical energy from an unregulated voltage and frequency source to a regulated voltage and frequency grid. The structure of the AC-DC-AC back-to-back converter is shown as Fig. 8, in which a configurable control for switch open faults of generator-side rectifier and grid-side inverter is involved. The AC-DC-AC controller also uses a buck–boost circuit to ensure the DC-link voltage constant. In addition, the resistances R1, R2 and R3 make up a crowbar protection circuit to improve the low voltage ride through capability of the PMSG. The main parameters of the PMSG are listed as follows:

Rated power: 6.75 kW; Rated voltage: 400 V;
Rated current: 10.8 A; Number of pole pairs: 2;
Rated frequency: 50 Hz; Rated speed: 1500 r/min;
Rated power factor: 0.9; Number of stator slots: 60;
Number of parallel stator branches: 2;
Minimum/Maximum air gap length: 0.5/10.2 mm;
Resistance of phase winding: 0.98 Ω.

Fig. 9 shows the hardware structure of the fault detection system. Current transformers, having turns of 50/5 A, are used in the laboratory setup with another three HCT204B current transformers. The produced voltage signals are sampled by using the data acquisition system (DAS). The current sampling circuit can be seen in detail in Fig. 9(b). The DAS is connected to a digital signal processor board via two communication links. One link is for multiplexing command purposes and the other for the analog to digital converter (A/D) of the DSP board. The DSP board is based on a Texas Instruments TMS320F2812 DSP chip. The DSP board is connected to a PC, which is equipped with corresponding development and debugging tools. In addition, three HPT205B voltage transformers are used for data acquisition together. In order to avoid aliasing problems, a low pass filter with a cut-off frequency 1.1 kHz is used. Furthermore, by using the OP295 dual operational amplifier, lower noise and higher accuracy of data acquisition can be assured.

B. Fault Diagnosis with Eccentricity

With the objective to simulate the eccentricity in the generator, an eccentric block is mounted on the rotary shaft in a coaxial way. Fig. 10 shows the vibration acquiring diagram, in which the block 1 denotes a B&K4371 accelerometer (0.844 mv/ms^{-2}), which is installed at the end of the stator top surface. Also, a B&K2636 vibration amplifier is used together with the system. Yokogawa DL750 ScopeCorder is utilized to save and transfer the vibration data and the generator speed to the PC for analysis purposes.

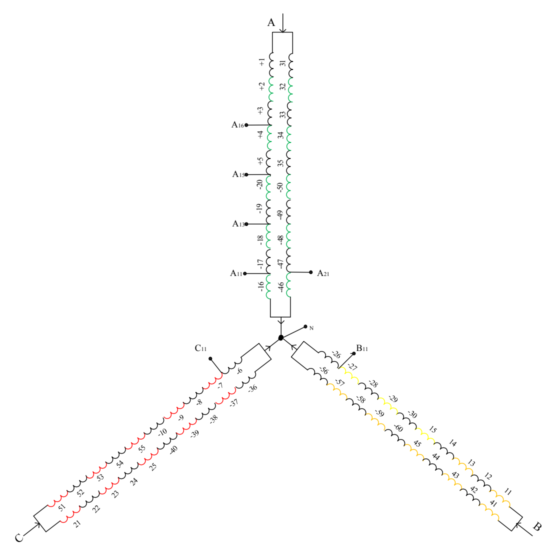


Fig. 7. Diagram of winding distribution.

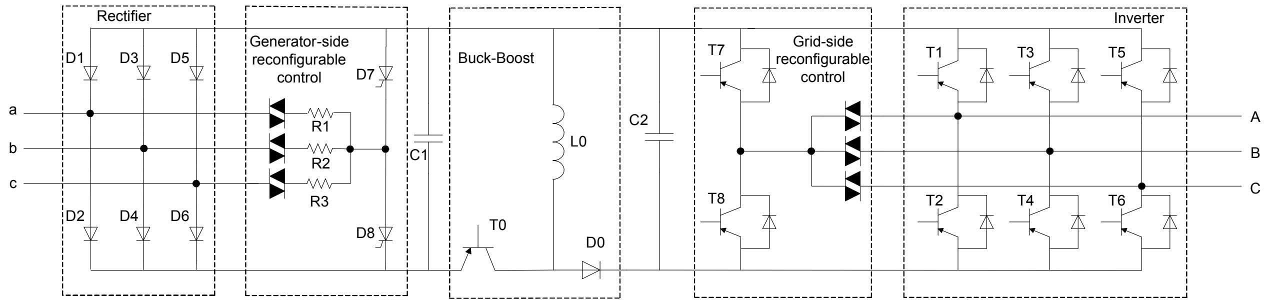


Fig. 8. AC-DC-AC controller.

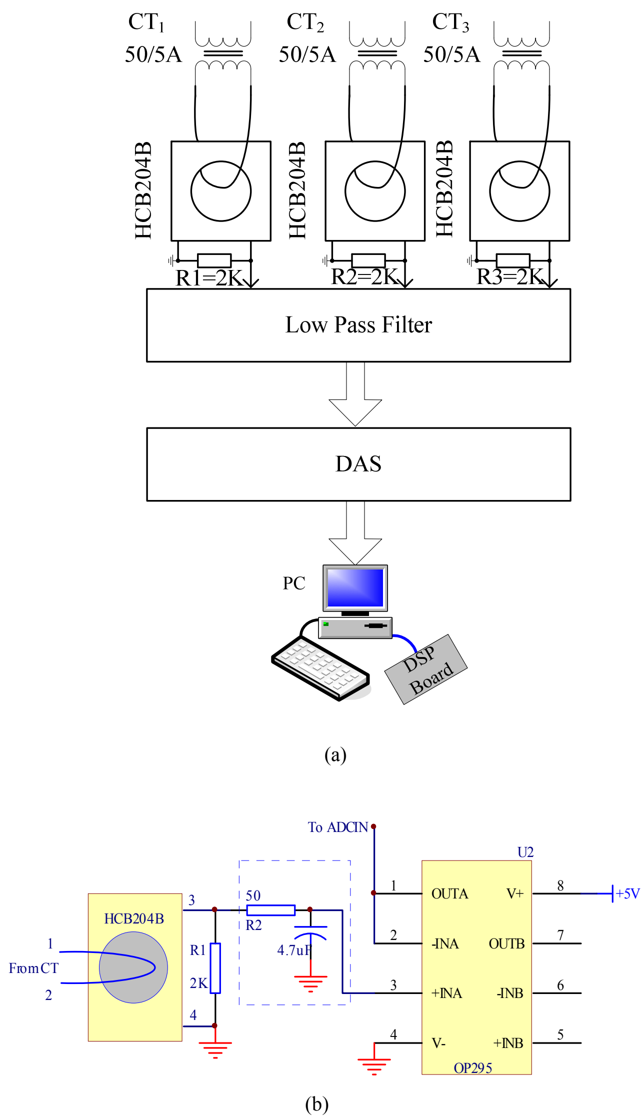


Fig. 9. Fault detection system: (a) hardware structure; (b) current sampling circuit.

Fig. 11 shows the frequency spectrum of the 17^{th} and 19^{th} order stator harmonic currents when the PMSG runs with an inter-turn short circuit (A_{11}-N) and a dynamic eccentricity hybrid fault. In the experimental test, the generator runs in grid-connected mode with a 2 kW/1 kVAR load. The corresponding frequency spectrum of the sideband frequency currents at 25Hz and 75Hz with same hybrid fault are shown in Fig. 12.

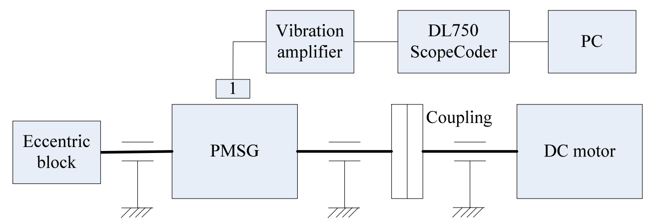


Fig. 10. Vibration acquiring diagram.

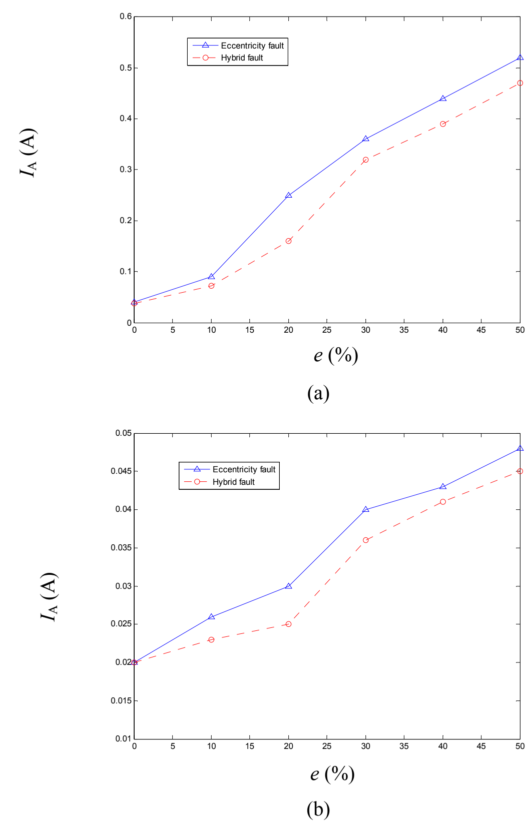


Fig. 11. Frequency spectrum of the 17th and 19th order stator harmonic currents (a) the 17th order; (b) the 19th order.

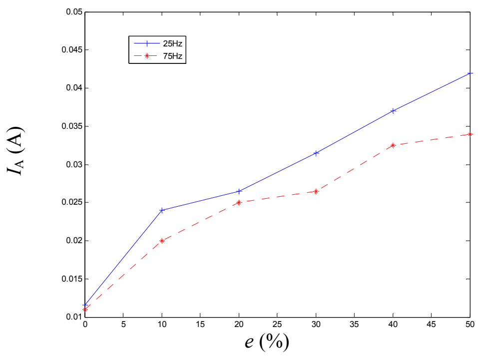


Fig. 12. Frequency spectrum of the 25Hz and 75Hz stator harmonic currents.

From Fig. 11, it can be observed that the 17th and 19th order stator current componets could also be used as the PMSG fault diagnosis characteristics with stator winding inter-turn short circuit (A_{11}-N) and dynamic eccentricity fault simultaneously.

The experimental results are in accordance with the simulation results presented in Fig. 4 and Fig. 5. The diagnosis with other inter-turn circuit fault locations has the similar results.

TABLE II
VIBRATION ACCELERATION OF STATOR VERTICAL DIRECTION

Fault modes	Amplitude of Vibration acceleration spectrum (mm/s^2)					
	50Hz	100Hz	150Hz	200Hz	250Hz	300Hz
A_{11}-N	0.014	0.202	0.014	0.020	0.015	0.081
A_{11}-A_{13}	0.019	0.304	0.019	0.022	0.018	0.083
A_{15}-A_{16}	0.015	0.246	0.016	0.021	0.014	0.081
A_{21}-A_{13}	0.020	0.256	0.018	0.022	0.020	0.082
A_{11}-B_{11}	0.016	0.321	0.015	0.023	0.021	0.085

Table II gives the amplitude of vibration acceleration spectrum at stator vertical direction with five different hybrid faults (e=10%). The five typical inter-turn short circuit faults located at A_{11}-N, A_{11}-A_{13}, A_{15}-A_{16}, A_{21}-A_{13}, and A_{11}-B_{11} respectively. As shown in table I, the change of the second order vibration acceleration spectrum component is distinct with this type hybrid fault. Thus, this can be another fault detection criterion for the hybrid fault in PMSG. From the vibration acceleration spectrum diagnosis shown in Table II, the conclusion obtained is that this kind of hybrid fault will be more difficult to be detected when the stator winding inter-turn short circuit fault location is produced closer to the generator neural point.

IV. CONCLUSION

In this paper, the stator winding inter-turn short circuit and dynamic eccentricity hybrid fault was modelled by using the FEM and the multi-loop circuit method, while taking the saturation phenomena into account. The controller had the ability of reconfiguration control with switch open faults. A crowbar protection circuit was used to enhance the he low voltage ride through capability of the PMSG. Moreover, the rotor eccentricity and stator winding inter-turn short circuit hybrid fault was studied experimentally by using an FFT technique, and some electrical and vibration results were achieved.

The online tests only need three current transformers to read the line currents and one accelerometer to obtain the vibration signal from the generator, and the digital algorithm is simple to implement by means of a low cost DSP. It will enhance the fault detection accuracy and can be run with other existing fault detection methods.

The main contribution of this paper is that the 17th and 19th order stator current components, and the sideband frequency currents at 25Hz and 75Hz, are used as fault characteristics for PMSG with stator winding inter-turn short circuit and dynamic eccentricity hybrid fault. In addition, it is pointed out that the second order vibration acceleration spectrum can be an auxiliary fault detection index. The effectiveness of these fault detection criteria were studied at different operating conditions.

It is pointed out that the severity of the inter-turn short circuit fault and dynamic eccentricity has great influence on the fault detection sensitivity. Although, less than 4% of inter-turn short circuit fault and less than 5% of dynamic eccentricity would not be detected easily by the proposed vibration tests; but it actually can be an auxiliary help for developing highly accurate fault detection system for PMSGs.

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