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Eccentricity Fault Detection in Permanent Magnet Synchronous Generators Using Stator Voltage Signature Analysis

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In this paper, an index is proposed for the detection of static eccentricity (SE), dynamic eccentricity (DE), and mixed eccentricity (ME) in a three-phase permanent magnet synchronous generator (PMSG). The proposed index is the amplitude of the sideband components with a particular frequency pattern which is extracted from the spectrum of the stator voltage. This index can be used in no load state prior to the loading of the generator which can cause damage in eccentricity conditions. Moreover, the proposed index works properly in loaded condition. Extraction of the proper indexes highly depends on precise computation of the necessary signals. Therefore, in order to fulfil the required precision, the time-stepping finite element method (TSFEM) is used to model the PMSG under eccentricity fault and to calculate the stator voltage as an appropriate signal for processing.

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1. Introduction

The use of renewable energy is rapidly increasing worldwide, mainly because the fossil fuels are non-renewable and will eventually run out. Among the renewable energies, the wind energy is popular due to its environmental benefits such as cleanness. While different generators are used in the wind turbines, permanent magnet synchronous generators (PMSGs) have been more favourable because of their advantages such as high efficiency, higher reliability which are the results of not using slip ring, disuse field excitation circuit and the ability of removing the gear box with increasing the number of the generator poles. The common faults in electrical machines include magnetic, electrical and mechanical faults.[1,2] Approximately, 80% of the mechanical faults lead to an eccentricity fault.

In a healthy motor, the symmetry axis of the rotor, the symmetry axis of the stator and the rotor rotating axis coincide with each other. In eccentricity conditions however, the mentioned axes are inconsistently displaced relative to each other, depending on the type of eccentricity. There are three types of eccentricities: static eccentricity (SE), dynamic eccentricity (DE) and mixed eccentricity (ME). In SE, the symmetry axis of the rotor coincides with the rotor rotation axis, but it is moved from the symmetry axis of the stator. In the mentioned case, the minimum air gap is constant and does not change with the rotation of the rotor. In DE, the symmetry axis of the stator coincides with the rotor rotating axis, but the rotor axis is moved corresponding to them. In dynamic eccentricity, the minimum air gap varies with the rotation of the rotor thus it is a function of the rotor position. In ME, both static and dynamic eccentricities exist simultaneously. In this case, all of the three mentioned axes are displaced relative to each other, and the air gap varies with the rotation of the rotor time dependently. Air gap eccentricity causes a ripple torque, which further leads to speed pulsations, vibrations, acoustic noise, and even an abrasion between the stator and rotor. Therefore, it is critical to detect air gap eccentricity as early as possible.[3]

In Ref. 4 some diagnostic techniques for fault detection have been reviewed. In Ref. 5 using a winding function approach, rotor current ripple and voltage harmonics have been used for the diagnosis of static eccentricity in no load salient-pole synchronous generators. In Ref. 6 a standard short-circuit test has been used to exploit offline current signature analysis, in order to detect eccentricity fault in salient-pole synchronous machines.

In Ref. 7 unbalanced radial force and magnetic flux density have been calculated analytically in the permanent magnet brushless dc motor (BLDC) under eccentricity. Ref. 8 compare dynamic responses and magnetic force respectively for surface mounted permanent magnet motor (SFPM) and interior permanent magnet motor (IPM) using FEM. In Ref. 9 an analytical method is used for the calculation of magnetic flux density in cylindrical magnetic actuator under eccentricity. In Ref. 10 an analytical approach has been used to diagnose eccentricity in axial flux permanent magnet synchronous generators for wind turbines. In Ref. 11 the cogging torque in PM brushless motors has been calculated analytically. In this method, magnetic field energy in the air gap has been used to obtain the cogging torque equation. The effect of eccentricity is also considered in the proposed method. In Ref. 12 vibration signature has been used in order to diagnose eccentricity fault in a synchronous reluctance machine. In Ref. 13, magnetically induced vibration associated with rotor/stator eccentricity has been studied and magnetic force and cogging torque have been calculated for various slot angles by using FEM. In Ref. 14 the effect of the non-uniform air gap on the various characteristics of doubly salient permanent magnet motor (DSPM) has been investigated via FEM and the flux density, inductance and torque in eccentricity condition have been calculated.

Eccentricity causes unbalanced magnetic force (UMF) which produces noise and vibration in electrical machines. The characteristics of the (UMF) of a BLDC motor due to uneven magnetization of a PM, rotor eccentricity, stator eccentricity and interaction between these factors, have been investigated experimentally and numerically in Ref. 15. The unbalanced magnetic pull (UMP) in ferrite magnet fractional slot BLDC motors due to either magnetic asymmetry or static rotor eccentricity, has been investigated in Ref. 16. In Ref. 17 the permanent magnet synchronous generator (PMSG) used in wind turbine has been modelled, considering rotor eccentricity and end-zone leakage field. The effect of static eccentricity on axial flux permanent magnet machines (AFPMMs) has been investigated in Ref. 18 by using a 3-D FEM, then the flux density distribution in the air gap and the total axial force between the rotor and stator are calculated. In Ref. 19 d-axis inductance has been used for air gap eccentricity diagnosis in PMSM, where it has been illustrated that Ld decreases as the eccentricity becomes more severe, due to the variations in the magnetic saturation. This parameter (Ld) has therefore been proposed as a fault index.

In this paper we use time-stepping finite element method (TSFEM) to study magnetic field distribution in the PMSG used in a wind turbine. Then using field distribution, other machine quantities such as the induced voltage, the stator current, inductance of the winding can be calculated. The accuracy of the fault diagnosis approach depends on taking into account the physical characteristics of the materials due to the considerable impacts they have on the fault diagnosis criteria.[20] As for TSFEM, different considered features such as the nonlinear characteristics of the ferromagnetic and PM materials, spatial distribution of the stator windings, geometrical characteristics of the stator slots and PMs can be used to model and analyze the healthy and faulty PMSGs under different types of eccentricity. Although, most of the references use current signature analysis to diagnose eccentricity in PMSG, in their method, loading of machine is necessary.[3,13,21] In a faulty machine, loading increases unbalance magnetic pull which may indeed expose the PMSG to further damage.[7,16] This is while the advantage of our proposed index is that eccentricity fault can be detected when the generator is not connected to the network and it is not loaded. It should be noted that the proposed method can be used in both loaded and no load condition because of the availability of the voltage signal in any loading level. In addition, the main advantage of the proposed index over other methods mentioned in the literature is its ability to diagnose eccentricity fault in no load status before further damage to the generator. Therefore, we consider voltage signature analysis to provide eccentricity fault diagnosis approach. In order to apply the proposed index to the real plant in practice, a voltage sensor with appropriate sampling frequency and data acquisition (DAQ) card can be used to import the voltage data to the computer. Then, fault diagnosis is done using different tools, such as the Fast Fourier Transform (FFT) to extract the related side band components in the spectrum of the voltage signal. In the next section, we begin presenting our model for the PMSG.

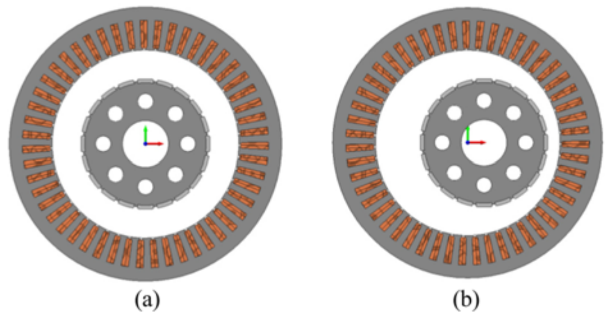

Fig. 1 Cross section of simulation PMSG (a) Healthy (b) SE

2. Modelling PMSG Using Time-Stepping Finite Element Method (TSFEM)

Precise modelling is the first step in the fault detection algorithms. Magnetic field calculation by FEM is one of the most accurate modelling methods. In this method, all of the machine's geometrical complexities are considered and nonlinearity of the material such as; ferromagnetic and permanent magnet are taken into account. Fig. 1 illustrates the cross section of the healthy and faulty PMSG under SE condition which modelled with Infolytica Magnet Package. Transient FEM has been used for the simulation of PMSG, and different eccentricity fault has been modelled in order to determine a suitable index for fault detection in PMSG. A medium speed (350 rpm) concentrated winding PMSG with 20 poles and 51 slots in the stator used in wind turbine is investigated in this paper and non-uniformity of the air gap due to the SE, DE and ME faults are modelled. In most of the references, the spectrum of the stator *current* is used as an index for eccentricity fault diagnosis in permanent magnet motors. In this paper, the spectrum of the stator *voltage* is proposed for eccentricity fault diagnosis in PMSG. The advantage of using the stator voltage is that eccentricity fault can be detected when the generator is not connected to the network and it is not loaded. This prevents exposition of the generator to further damage. The PMSG is rotated in nominal speed and no load voltage is used as the fault detection index.

Maxwell's equation for PMSG can be written as a follow:[22]