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Application of cyclic coherence function to bearing fault detection in a wind turbine generator under electromagnetic vibration

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ABSTRACT

In a wind turbine generator, there is an intrinsic electromagnetic vibration originated from an alternating magnetic field acting on a low stiffness stator, which modulates vibration signals of the generator and impedes fault feature extraction of bearings. When defects arise in a bearing, the statistics of the vibration signal are periodic and this phenomenon is described as cyclostationarity. Correspondingly, cyclostationary analysis enables finding the degree of cyclostationarity representing potential fault modulation information. In this paper, the electromagnetic vibration acting as a disturbance source for fault feature extraction is deduced. Additionally, the spectral correlation density and cyclic coherence function used for vibration analysis are estimated. A real 2 MW wind turbine generator with a faulty bearing was tested and the vibration signals were analyzed separately using conventional demodulation analysis, cyclic coherence function, complex wavelet transform and spectral kurtosis. The analysis results have demonstrated that the cyclic coherence function can detect the fault feature of inner race successfully, while the feature is concealed by intensive electromagnetic vibration in the other three methods. The disassembled bearing of the wind turbine generator illustrates the effectiveness of the analysis result, and precautionary measures for protecting bearings in generators are suggested.

1. Introduction

Wind energy plays a significant role in renewable energies worldwide. Especially in China, 30.8 GW of new installed capacity was increased in 2015, once again the highest annual number for any country ever [1]. Meanwhile, the reliability and safety of wind turbines are attracting more and more attentions from both operators and manufacturers because of their decisive effect on operation cost and power efficiency [2]. As a result of suffering extreme temperature difference and alternating loads, a wind turbine drive train which consists of a rotor hub, a gearbox and a generator easily fails making its health conditions necessary to be monitored and diagnosed duly [3–5].

The generator is positioned on the end of the wind turbine drive train. High rotational speed, electromagnetic vibration, misalignment with the gearbox and shaft current corrosion etc. may damage stator winding, rotor winding or the bearing in the generator. In wind turbine generators greater than 1 MW, the bearing is the most frequent failure part [6], which can induce catastrophic results such as rubbing or even scrapping in generators. Consequently, numerous approaches have been proposed to

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detect bearing fault in generator. Mathew and Alfredson [7] reviewed the bearing fault signatures with a view to detecting incipient failure based on vibration measurements. Afterwards, the vibration analysis for bearings was extended and supplemented continually [8–10]. Kusiak and Verma [11] used historical temperature measurements to develop a neural network and predicted over-temperature faults of bearings up to 1.5 h before their occurrence. Onel and Benbouzid [12] applied Park transform and Concordia transform of stator current to find the bearing fault feature in induction motors. Bulter [13] described a shock pulse method (similar to vibration analysis) to detect faults in rolling bearings. Shiroishi et al. [14] investigated the severity and location of a bearing defect using acoustic emission. Tandon [15] analyzed several techniques above and summarized the limit size of defect that can be detected by different methods.

Comparing the aforementioned methods of defect detection, vibration analysis is the most direct and effective way for bearing condition monitoring in wind turbine generators since it can make a compromise between equipment cost and diagnosis accuracy. Massive processing methods for vibration signal were applied to detect bearing fault. Commonly, demodulation analysis combined with band-pass filtering were regarded as a classic tool to detect the modulation components hidden in the resonance frequency band [16,17]. However, the selection of the resonance band needs human interference, which results in inaccurate diagnosis. To this end, Antoni and Randall [18] proposed spectral kurtosis which can decompose signal into different frequency bands and regard the band with maximum kurtosis as the optimal filtering band. To evidence the fault impact of bearings in vibration signals, an autoregressive model and minimum entropy deconvolution were developed to restrain the periodic components from gear mesh and background noise [19,20]. Borghesani et al. applied the cepstrum pre-whitening proposed by Randall [21] to diagnose bearing faults under variable speed conditions [22]. Rai and Mohanty [23] detected bearing fault using FFT and Hilbert-Huang transform based on the ability of nonstationary signal processing. Park et al. [24] proposed the minimum variance based cepstrum for early fault detection in automotive ball bearings.

In real industry application, the statistics of the vibration signal correlating to a faulty bearing are generally periodic, and the signal is identified as cyclostationary due to random slips, speed fluctuations, and variations of the axial to radial load ratio. Antoni [25] discussed three propositions of cyclostationary analysis in rotating machines and promoted them more applicable in practice [26]. Bearing fault detection [27], Gear degradation indication [28], and other applications in pumps and diesel engines etc. [29] have validated the capability of cyclostationary analysis. However for wind turbines, researchers preferred to employ nonstationary methods to analyze gear or bearing faults such as wavelet analysis [30], empirical mode decomposition [31] etc., rather than cyclostationary analysis. In this paper, an intrinsic electromagnetic vibration (EV) in wind turbine generators, caused by an alternating magnetic field acting on a low stiffness stator, is investigated. This EV can modulate the vibration signal of the generator and impede the fault feature extraction of bearings. The demodulation ability of cyclostationary analysis is discussed. A cyclic coherence function based on cyclostationary analysis is applied to detect bearing fault in a wind turbine generator under intensive EV.

The organization of this paper is as follows. The principle of double fed induction generators and the characteristics of wind turbine drive trains are introduced in Section 2. The intrinsic electromagnetic vibration in wind turbine generator is deduced in Section 3. In Section 4, second order cyclostationary analysis is reviewed, and the corresponding spectral correlation density with cyclic coherence function are estimated. In Section 5, a real 2 MW wind turbine with a faulty bearing in its generator is tested, the vibration signals are analyzed using cyclic coherence function, complex wavelet transform and spectral kurtosis. The failure mechanism of the bearing is discussed. The conclusion is drawn in Section 6.

2. Double fed induction generator

The gearbox driven wind turbine is the main type within the category of horizontal axis wind turbines whose drive train is shown as in Fig. 1a. Stochastic winds are absorbed by blades and wind energy is converted into mechanical energy in the rotor hub with low rotational speed, then the low rotational speed is accelerated through the gearbox to drive the generator with high speed. The gearbox, which consists of a planetary stage (a sun gear, planet gears, and a ring gear) and two stages of ordinary gears, has both compact structure and large transmission ratio. The blades and rotor hub are supported by the main bearing. According to the characteristics of the drive train, acceleration transducers are attached on seven different positions to monitor the health states of the gears and bearings shown in Fig. 1a.

The double fed induction generator (DFIG) is employed comprehensively in gearbox driven wind turbines, whose operation mode is shown in Fig. 1b. The stator windings are connected to a power grid directly through a transformer, and active power is transferred all through from the stator to grid. Unlike stator windings, rotor windings are connected to the power grid using an inverter that can regulate slip power on the basis of the rotational speed of the rotor. If this rotational speed is lower than the synchronous speed of the generator, rotor absorbs power from the grid. On the contrary, rotor sends power to the grid at ultra-synchronous speed.

3. Electromagnetic vibration in wind turbine generators

Electromagnetic vibration (EV) is an intrinsic phenomenon originated from alternating deformation of the stator of generators. As shown in Fig. 2a, the three phase currents in stator windings are denoted by i_A, i_B and i_C, among which there are 120° phase differences. The three phase windings are placed symmetrically shown as in Fig. 2b to e where AX denotes A phase, BY denotes B phase and CZ denotes C phase. A, B and C in Fig. 2b–e are defined as input directions when the corresponding currents are positive. Otherwise, A, B and C are output directions when the currents are negative.