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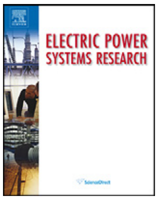

Experimental validation of doubly fed induction machine electrical faults diagnosis under time-varying conditions

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ABSTRACT

This paper investigates a new diagnosis technique for incipient electrical faults in doubly fed induction machine for wind power systems under time-varying conditions. The proposed method is based on currents frequency sliding pre-processing, and discrete wavelet transform thereby. The mean power calculation of wavelet signals, at different resolution levels, is introduced as a dynamic fault indicator for quantifying the fault extents. The approach effectiveness is proved for both stator and rotor faults under speed and fault varying conditions. Simulation and experimental results show the validity of the developed method, leading to an effective diagnosis procedure for stator and rotor faults in doubly fed induction machines.

1. Introduction

For many modern large wind farms, wind turbines equipped with doubly fed induction machine (DFIM) are a well established technology. Different diagnosis methods have been proposed for wind turbines using DFIM [1–4]. Investigations on different failure modes in variable speed induction motors done by industrials and experts have revealed that 45% of motor failures are related to the stator and rotor parts [5]. A detailed analysis of this type of faults can be found in [6]. More concretely, each electrical fault that occurs in the stator/rotor side of a DFIM (short circuits or increasing resistance) give rise to a phase dissymmetry because the impedances of the windings are not longer equal or because of a distortion in the airgap flux. Thus the simplest way to emulate a phase unbalance in order to test the effectiveness of diagnosis methods is to insert an additional resistance in series to one phase stator/rotor winding [4] to provoke a phase unbalance.

Increasing resistance, or as commonly known in the literature “High-Resistance Connections”, is a common problem that can occurs in any power connections of industrial motor [4,7]. This failure mode can be initiated by gradual abrasion, corrosion and fretting, leading generally to a local heating which in turn leads to insulation damage. Consequently if the evolution of this type of faults is not detected at an incipient stage, its propagation can lead to more serious failure modes. Several diagnostic methods, such as motor current signature analysis (MCSA), and more recently, flux signature analysis (FSA) and rotor modulation signature analysis (RMSA) have been proposed to detect stator and rotor faults [8–13].

Depending on wind speed, the induction machine operates continuously in time-varying condition. In this context, the classical application of Fourier analysis (FA) for processing the above signals fails as slip and speed vary. Thus the fault components are spread in a bandwidth proportional to the variation. Among different solutions, high resolution frequency estimation [12] and more recently signal demodulation (SD) technique [13] have been developed to reduce the effect of the non periodicity on the analyzed signals. These techniques, based on FA gives high quality discrimination between healthy and faulty conditions but don’t provide time-domain information. This shortcoming in the Fourier analysis can be overcome to some extent by analyzing a small section of the signal at a time by means of short-time Fourier transform (STFT). This method was widely used to detect stator and rotor failures in induction motor. As an advanced use of the FFT algorithm, it assumes local periodicity within continuously translated time window. However the fixed size of the chosen window, the difficulties in quantifying the faults extent and the high computational cost required to obtain a good resolution still remain the major drawbacks of this technique [14–16]. wavelet transform (WT), on the other hand, provides greater resolution in time for high frequency

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components of a signal and greater resolution in frequency for low frequency components. In this sense, wavelets have a window that automatically adjusts to give the appropriate resolution developed by its approximation and detail signals.

Motivated by the above proprieties, WT was used with different approaches for the diagnosis of anomalies in induction machine such as: undecimated discrete wavelet transform [17], wavelet ridge method [18] and wavelet coefficients analysis [1,19,20] for stator and rotor fault detection. More intensive research efforts have been focused on the use of approximation and detail signals for extracting the contribution of fault frequency components in case of broken bars [14,21–23], inter-turn short-circuits [14,22], mixed eccentricity [22,24], and increasing resistance in stator phase [4,17,25,26] or rotor phase [4,27]. Most of the reported contributions are based on wavelet analysis of the currents during start-up or load variation for diagnosis purposes. In this context, the frequency components are spread in a wide bandwidth as slip and speed vary considerably. The situation is more complicated under rotor faults due to the proximity of the fault components to the fundamental one. These facts justify the common use of multi-detail or/and approximation signals resulting from wavelet decomposition, whose levels are imposed by the sampling frequency. This dependency on the appropriate choice of the sampling frequency and tracking multi-fault components on multi-frequency bands complicate the diagnosis process. Moreover, the use of large frequency bands subjects the detection procedure to erroneous interpretations due to possible confusion with other harmonics related to the common use of gearboxes [8] in wind turbines. In order to quantify the fault severity, the energy content of approximation and/or detail signals resulting from wavelet decomposition were used in [14,22]. But this attempt reduces each time–frequency band to a single value. In such a way the time-domain information is lost. Motivated by the above discussion, the possible improvements can be formulated as follows:

- A low sampling frequency can be used to reduce the memory required.
- Successive frequency sampling should be avoided in order to reduce latency in time processing.
- More precision in removing the effects of the fundamental component and other harmonic effects around the most relevant fault component is required.
- The contribution of the most relevant fault frequency components under time-varying conditions can be clamped in a single frequency band.
- Monitoring the fault severity evolution dynamically over time is mandatory for variable speed-constant frequency control strategy using DFIM.

In this paper, a simple and effective method is presented to solve the above open points for the diagnosis of electrical faults in DFIM under time-varying conditions. A new approach based on currents pre-processing by frequency sliding (FS) and discrete wavelet transform (DWT) thereby is here proposed [26,27]. Once the state of the machine has been qualitatively diagnosed, a dynamic mean power calculation, at the resolution level of interest, is introduced as a diagnostic index for fault quantification over time. The efficiency of the proposed approach for fault detection and quantification is proved by simulations and experiments. The results on stator faults presented in this paper have to be considered as an extension to those presented in [26]. Moreover, in this work, new stator fault configurations are investigated and the method is effectively applied also for the detection of rotor faults in time-varying conditions.

The paper is organized as follows. In Section 2 the fault phenomenon is described in time and frequency domains. Section 3 presents the proposed approaches based on wavelet transform. Simulation and experimental results are presented and commented in Sections 4 and 5 for stator faults and in Section 6 for rotor faults under time-varying conditions. Once the state of the machine has been qualitatively diagnosed under different fault configurations, the corresponding quantitative evaluation results are presented and discussed in Section 7. Finally, conclusions are given in Section 8.

2. Modeling and phenomenon description

A doubly fed induction machine three-phase model has been implemented in Matlab–Simulink. As described in [28], this model is based on the representation of the DFIM as a rotating transformer. The model was adapted to allow a great flexibility in managing all the machine parameters in order to simulate any stator or rotor asymmetry configuration during speed transients. In order to validate the results from the simulation model, an experimental investigation was conducted using a doubly fed induction machine. The main characteristics of the tested motors were: rated stator voltage: 380 V, rated rotor voltage: 186 V, rated power: 5.5 kW, 2 pair of poles, nominal stator current: 15.3 A, nominal stator current: 19.5 A, rated speed: 1400 rpm, stator phase resistance: 0.531 Ω, and rotor phase resistance: 0.31 Ω.

The induction machine is coupled to a 9 kW separately excited by a DC machine, supplied via a commercial DC/DC chopper used to realize speed transients. Stator and rotor currents are sampled with a 3.2 kHz sampling rate by means of a DS1103 dSpace Board. The unbalances on stator and rotor side were obtained by additional resistances (R_{add}) connected in series to one phase winding both in simulation and experimental tests.

The DFIM, like any other rotating electrical machine, is subjected to both electromagnetic and mechanical forces symmetrically repartitioned. In healthy condition the three stator and rotor phase impedances are identical, and then currents are symmetrically generated. Under these normal conditions, only fundamental frequencies f and sf exist respectively on stator and rotor currents (f: supply frequency, s: slip). If the stator part is damaged, the stator symmetry of the machine is lost producing a reverse rotating magnetic field. This dissymmetry generates magnetic forces on the rotor, caused by the change in the magneto-motive force from the unbalanced stator phase. More precisely, in the case of stator asymmetry, the stator currents produce a counterrotating magnetic field at the frequency $-f$. This component induces a rotor current component at $(2-s)f$. These frequency components generate electromagnetic and mechanical interactions between stator and rotor (Fig. 1). Consequently, a torque and speed ripples that modulate the rotating magnetic flux are generated at frequency $2f$. This modulation leads to an additional component at frequency $(2+s)f$.

The new rotor harmonic component $(2+s)f$ interacts with the arising torque and speed ripples at frequency $2f$ and give rise to new stator current harmonics at the frequencies $\pm 3f$. Which in turn induces reaction on rotor parts and generate a new frequency component at $(4-s)f$ on the rotor side. This chain of interactions leads to the appearance of new harmonic components $((f_{ksa})_s = \pm kf)_{k=1,3,5,...}$ and $((f_{kra})_s = (2k \pm s)f)_{k=1,2,3,...}$ in the stator and rotor currents respectively.

Practically, in squirrel cage induction machine whose rotor currents are not accessible, the focus has been always on the tracking of the 3rd and the 5th harmonic components $((f_{ksa})_s = \pm kf)_{k=3,5}$ using DWT [14,24]. But these components are naturally damped by the effect of machine-load inertia on high order fault harmonics (Fig. 1). In Section 3, a simple new method for an efficient tracking of the first and the most relevant stator fault component $((f_{ksa})_s = -kf)_{k=1}$ is proposed using DWT.