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Impacts of rotor inter-turn short circuit fault upon performance of wound rotor induction machines

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ABSTRACT

This paper investigates the performance of a wound rotor induction motor (WRIM) under rotor inter-turn short circuit (SC) fault. Magnetic equivalent circuit (MEC) and finite elements method (FEM) are used to model the machine. Impacts of the fault on the signals of the machine including rotor current, stator current, and developed torque of the motor are addressed. Current of SC turns is also the signal that is considered here. A method based on the MEC is used to estimate different inductances of WRIM in which the impact of yokes, stator and rotor tooth, windings distribution and also core saturation are included. The obtained inductances are compared with that of the FEM and effect of the SC turns on the inductances are investigated. Finally, the fault is diagnosed using Fourier transform of the stator current and verified by experimental results.

1. Introduction

Induction motors are widely used in industry due to their simple structure, high robustness and high reliability. However, wound rotor induction motor (WRIM) has less application compared with squirrel-cage induction motor (SCIM). The major disadvantage of WRIM is the required intensive maintenance and high cost of repair for the components such as slip rings and brushes. Nevertheless, WRIM has a number of advantages leading to its applicability in some cases [1,2]. Among these advantages, its capability in developing a high starting torque at low starting current by inserting an external resistance in series with the rotor winding is the most important advantage. In addition, it is possible to control the rotor currents in the range of 60–100% of the rated speed using a power electronics converter, where the rating of the converter is a fraction of the motor rated power. However, these advantages lead to the industrial applications of high power (generally higher than 1000 hp) WRIMs [1–3]. In fact, these large motors are expensive, sensitive and difficult to repair. General industrial applications of WRIM include ball and sag mills, chippers or hoists, conveyors, fans and blowers, pumps and cranes [4]. Nowadays, wound rotor induction machine is used in wind turbines and specifically in large wind farms as generator which is called doubly-fed induction generator (DFIG) [5]. Considering the ever increasing of application of this generator, appropriate condition monitoring system is essential for the machine. This system enables to recognize the fault in the initial stages and prevents the serious damages to the machine and its relevant systems.

The common faults in WRIM consist of bearing fault, eccentricity fault and faults related to SC and open circuit of the stator and rotor windings, brushes and slip rings faults [6].

This paper concentrates on the rotor SC turns fault. In [7], the electromagnetic characteristic and rotor vibrations characteristic of a turbine-generator under similar fault has been investigated. A radial basis function neural network has been used in order to present a method for diagnosing rotor SC turns fault. Finally, the results have been verified experimentally which show the capability of the introduced method for diagnosing the fault and detecting the number of faulty turns.

In [8], an on-line diagnosis method has been implemented using a search coil in the rotor winding of the turbo-generator. This method uses the induced voltage of the coil and motor noise characteristic and it employs wavelet analysis beside Mallatpsilas local maximum de-noising algorithm which ultimately leads to fault diagnosing and locating. The theoretical and experimental results show the capability of method in fault detection.

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Table 1
Specifications of Simulated WRIM.

Name plate details		Stator outer diameter	353
Power (kW)	7.46	Stator inner diameter	228.15
Speed (rpm)	1425	Rotor outer diameter	227.15
Frequency (Hz)	50	Air gap length	0.5
Stator voltage$_{L\text{-}L}$ (V)	$420\sqrt{3}$	Stator slots Number	48
Stator rated current rms (A)	8.57	Stator slot opening	2.5
Rotor rated current rms (A)	26.1	Turns per slot in series	34
Poles	4	Stator slot depth	26.82
Slip (pu)	0.05	Stator tooth width	8.22
Rph stator (DC, cold)	1.67 Ω	Stator tooth tip depth	1
Rph rotor (DC, cold)	0.2 Ω	Rotor tooth tip depth	1
Rotor inertia (kg/m^2)	0.21	Rotor slot opening	2
	Geometry (mm)	Rotor slot depth	22.5
Axial length rotor core	103.9	Rotor slot width	3.5
Axial length stator core	100.9	Rotor Turns/coil in series	6
Shaft diameter	120	Rotor slots Number	72

In [9], similar with [8], wavelet transform and search coil has been used to detect the rotor SC turns fault in a turbo-generator. At this end, magneto-motive force (mmf) signal and noises signal of coils have been analyzed and simulation results presented.

In [10], bi-spectrum analysis has been successfully applied to analyze SCIM and monitor its condition using the vibrations signal. In [11], also bi-spectrum analysis of stator current signal has been used in a turbo-generator which is generally much better signal than the vibrations signal for fault detection and less affects by noise.

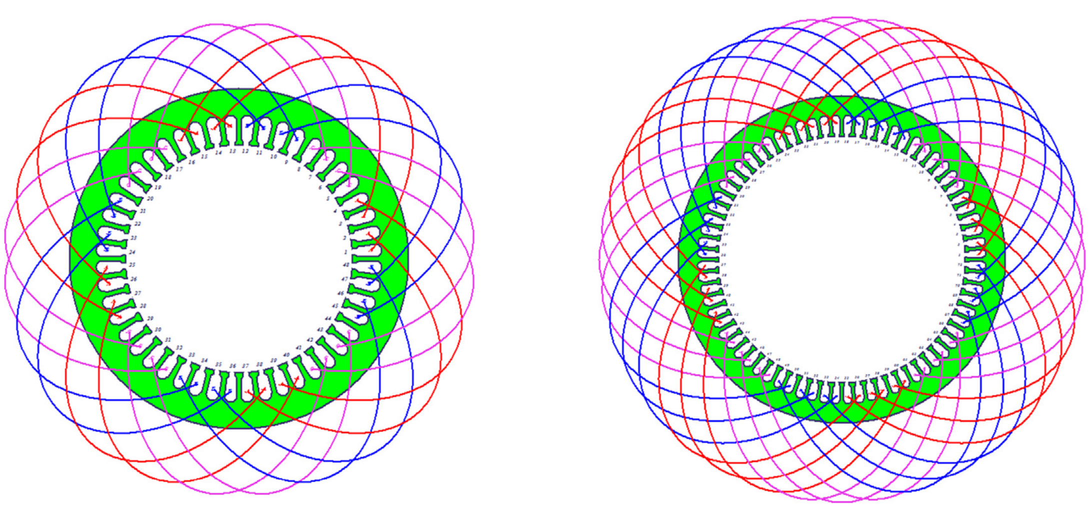
As discussed above, the presented methods are often applied to turbo-generators and signals such as vibrations are employed. Generally, measuring vibrations signal is difficult and costly (needs expensive sensors) and the signal is considerably under influence of noise. In some cases search coil is employed, but it is difficult to fix it in the machine and sometimes the fixing location affects the fault detection.

The aim of this paper is to investigate the impacts of the rotor inter-turn SC fault on the performance and different signals of a WRIM. At this end, two modeling methods are employed which are described in Sections 2 and 3. In Section 4, inductances of the motor are estimated by MEC method and effects of fault on these inductances are studied. In Section 5, impacts of the fault on the time domain signals of machine such as stator and rotor currents and developed torque have been considered. In this section, fault current and inductance of faulty phase have been presented. Amplitude of harmonics related to the fault is considered in Section 6 and two frequencies are introduced for fault diagnosis in this section. Rotor inter-turn SC fault is implemented in a real machine and the proposed theoretical methods are verified experimentally. Finally, Section 8 concludes the paper.

2. Finite elements based simulation

For finite elements based simulation of WRIM Ansoft Maxwell software has been used. Specifications of the simulated WRIM have been summarized in Table 1. First a pre-simulation is carried out in RMxprt environment in which there is possibility to enter the precise geometry of the motor, particularly stator and rotor windings. In this way, the impact of the end effect upon the inductances of the motor is estimated which is not possible to calculate it in 2D case. Fig. 1a shows the stator winding configuration and Fig. 1b presents the rotor winding configuration.

Then simulation is transferred to 2D environment and the estimated inductances due to the end effect are added to the stator and rotor phase inductances. In the simulation, the rotor excitation is taken to be zero because of SC of the terminals of the rotor phase. Fig. 2 shows the machine geometry as well as its meshing. It has about 55000 nodes mainly concentrated in the air gap and windings, particularly faulted rotor winding. Fig. 3 presents the flux density pattern within the machine.



(a) (b)

Fig. 1. (a) Stator and (b) Rotor winding in RMxprt environment.