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Static air-gap eccentricity fault diagnosis using rotor slot harmonics in line neutral voltage of three-phase squirrel cage induction motor

Mohamed El Kamel Oumaamar, Yassine Maouche*, Mohamed Boucherma, Abdelmalek Khezzar

Laboratoire d'électrotechnique de Constantine, Department of Electrical Engineering, University Constantine 1, 25000 Constantine, Algeria

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ABSTRACT

The mixed eccentricity fault detection in a squirrel cage induction motor has been thoroughly investigated. However, a few papers have been related to pure static eccentricity fault and the authors focused on the RSH harmonics presented in stator current. The main objective of this paper is to present an alternative method based on the analysis of line neutral voltage taking place between the supply and the stator neutrals in order to detect air-gap static eccentricity, and to highlight the classification of all RSH harmonics in line neutral voltage. The model of squirrel cage induction machine relies on the rotor geometry and winding layout. Such developed model is used to analyze the impact of the pure static air-gap eccentricity by predicting the related frequencies in the line neutral voltage spectrum. The results show that the line neutral voltage spectrum are more sensitive to the air-gap static eccentricity fault compared to stator current one. The theoretical analysis and simulated results are confirmed by experiments.

1. Introduction

Nowadays, three-phase squirrel cage induction motors are the mostly used type of electrical machines regarding their reliability and low cost. However, the induction motor can be subjected to internal and external influences of various natures which leads to their low performances.

Many types of squirrel cage induction motor faults have been referred to the literature:

1. Stator winding faults [1–4].
2. Rotor faults (e.g., broken bar or rotor constructional asymmetry) [5–13].
3. Rotor mechanical faults (e.g., bearings, misalignment and eccentricity between the stator and rotor) [14–23].

In order to detect these faults many machine parameters have been used in the literature. The most monitored parameters include Stator Current Signature Analysis, vibration monitoring, torque, temperature measurement cited in [24] and line

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[*] Corresponding author.

E-mail addresses: mohamed-el-kamel.oumaamar@lec-umc.org (M.E.K. Oumaamar), yassine.maouche@lec-umc.org (Y. Maouche), mohamed.boucherma@lec-umc.org (M. Boucherma), abdelmalek.khezzar@lec-umc.org (A. Khezzar).

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neutral voltage signature in [25]. In [26] the zero-sequence current have been used to detect static air-gap eccentricity in delta-connected induction motors.

The predominant method found in the literature is the Motor Current Signature Analysis (MCSA). The line neutral voltage differs from (MCSA) method in that it gives more harmonic diagnosis signatures with higher amplitudes under broken bar fault [27–29].

To get a correct diagnosis, it is necessary to have a detailed mathematical model which can predict the induction motor state condition. For example, the model based on Winding Function Approach (WFM) in [30–33], or on Finite-Element Method (FEM) in [34] and [35]. The main advantage of using (WFM) model is that it allows an analytical study of the generation mechanisms of different harmonics. The (WFM) model has been used in [36] to develop a mathematical model that enables numerical modeling taking into account the presence of static air-gap eccentricity. In [37], the (WFM) has been extended to a 3D considering the axial non uniformity caused by slot skewing or axial eccentricity.

In healthy state, the harmonic components in the stator current spectrum are induced by the discrete distribution of rotor currents in a finite number of slots, and the permeance variation in the air-gap (permeance harmonics). These harmonic components are usually called Rotor Slot Harmonics (RSH) [38]. Their orders are defined by:

$$\left\{ h_{RSH} = (6k \pm 1)_{k=1,2\ldots} \cap h_{RSH} = \left(\frac{\lambda n_b}{p} \pm 1 \right)_{\lambda=1,2\ldots} \right\} \tag{1}$$

In faulty state, several deficiencies have been recognized in research endeavors, among which we distinguish the broken bar. This last has been detected by monitoring the additional RSH components that result from the variation of discrete distribution of rotor geometry. In [39,40] the permeance variation resulting from the air-gap eccentricity in induction machines produces supplementary RSH components related to pure static or to pure dynamic eccentricity in a particular combination of stator and rotor windings configuration (poles-pair and a rotor slots number). The equation that describes such components is [39]:

$$h_{RSH}^{ecc} = \left(\frac{\lambda n_b \pm n_d}{p} \pm 1 \right)_{\lambda=1,2\ldots} \tag{2}$$

when $n_d = 1, 2, \ldots$, this has to do with pure dynamic air-gap eccentricity; conversely, when, $n_d=0$ this refers to pure static air-gap eccentricity.

On the other hand, spectral components can be observed around the fundamental in the case of the presence of both static and dynamic eccentricities, which are given by [39]:

$$f_{mix} = f_s \pm f_r \tag{3}$$

The more reliable signatures generated by the static air-gap eccentricity fault are in some cases at higher frequencies which makes them difficult to notice using MCSA method. However, the amplitudes of the higher frequencies are more pronounced in the line neutral voltage spectrum.

The aim of this paper is to present an alternative method based on the analysis of the line neutral voltage taking place between the supply and the stator neutrals in order to detect air-gap static eccentricity fault, which will be of high interest to manufacturers, in order to prevent serious problems caused by build up phases and assembly tolerances. As an example, Thomson and Barbour in [42] reported that for a typical air-gap length in a 2 MW, 4-pole, induction motor is 2.5 mm with a permissible maximum tolerance of 10% eccentricity, the static and dynamic eccentricities will have a maximum permissible level of 8.0% and 2.0% respectively. For that, they found necessary to identify the level of static eccentricity, and they used a finite element results to compare with experimental ones. The drawback of using a particular model for each motor, and the difficulty to implement this solution for online diagnosis, did not prevent the authors in [18,34,42,44], to find that the obtained results can have a large industrial application.

Furthermore, as the static eccentricity causes an unbalanced magnetic pull, which is usually in the direction of the greatest air-gap flux density. The level of this unbalance is required for calculating the stiffness of the mechanical assembly and deciding the factor in the size of bearings required to transmit this radial force [18,21,42,43,45]. In addition, the high level of static eccentricity can cause, in plus of the high vibration at the bearings and subsequent bearing failure, the dynamic eccentricity and also the rotor to stator rub [18,21,42,43,45].

On the other hand, it is reported in the literature the difficulty to quantify the level of the static eccentricity, or to separate it from the dynamic one [18,21,45]. The authors in this paper propose an original way based on the analysis in the frequency domain of the line neutral voltage which can quantify the static eccentricity level for online or offline diagnosis purposes, even with the presence of dynamic one.

The paper is made up of six main sections. Section 1 has to do with a general introduction. Section 2 deals with the analytical model of three-phase induction motor. Section 3 discusses the RSH harmonic components of line neutral voltage in healthy state. Section 4 explains the mechanism of generation of additional RSH harmonic components induced by the static air-gap eccentricity. Section 5 encompasses the presentation of the obtained experimental results, as well as the validation of the analytically predicted RSH harmonics. Section 6 is devoted to a general conclusion for this paper.