Effects of Eccentricity on External Magnetic Field of Induction Machine

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Abstract—This paper deals with the analysis of external magnetic field of three-phase induction motor in order to diagnose the air gap asymmetry caused by eccentric rotor. Dynamic eccentricity produces low frequency air gap flux components, however they can be observed in stator current only under mixed eccentricity. Unlike MCSA (motor current signature analysis), described method allows to detect purely dynamic eccentricity or to detect dynamic eccentricity under mixed eccentricity with a minimal effect of static eccentricity. Although many papers have been focused on external magnetic field analysis, they have usually described other types of faults. In this paper the amplitudes of characteristic frequency components are predicted using FEM and some obtained results are verified by measurement. Both purely dynamic and mixed eccentricities are taken into account as well as saturation of magnetic circuit due to its significant influence on calculated spectrum.

I. INTRODUCTION

The monitoring and diagnosis of electric machines have been targets of extensive research activities for years as a way to improve the reliability of industrial processes and to reduce claims caused by unexpected faults. It is not surprising that the diagnostic techniques have been most often developed for induction machines because of their dominant position in industry.

The air-gap eccentricity of induction motor is adverse phenomenon and usually occurs due to necessary tolerances in manufacturing process. Generally the eccentricity of up to 10% is permissible and it should not have significant influence on motor characteristics and lifetime [1, 2]. However, the higher level of eccentricity gives rise to unbalanced magnetic pull (UMP) and therefore noise, vibration and excessive bearing wear occur [3-5]. In exceptional cases, combination of UMP and shaft bending can cause stator to rotor rub.

The air-gap eccentricity can appear as a static and dynamic, however both types usually exist together. The static eccentricity occurs if centre of rotation is concentric with rotor axis but outside the stator bore axis and the dynamic eccentricity occurs if centre of rotation is outside the rotor axis but concentric with stator bore axis (Fig.1). When the centre of rotation is between stator bore axis and rotor axis, both types of eccentricity are presented simultaneously (mixed eccentricity). In other words, the minimal air-gap length is stationary in case of static eccentricity and rotates with the rotor in case of dynamic eccentricity. The level of rotor eccentricity is usually quantified relatively to the nominal air gap length.

II. AIR-GAP FLUX AND MSCA

The rotor eccentricity produces the additional air-gap field components, which can be derived from air-gap permeance and Ampere’s Circuital Law. This derivation has been performed by several authors [6] and it is known that static and dynamic eccentricity produce $p \pm 1$ pole pairs in spatial distribution of magnetic field in the air-gap, where $p$ is fundamental pole pair number. Important difference between magnetic field components related to static and to dynamic eccentricity is in angular velocity. Whereas the angular velocity of components produced by the static eccentricity is equal to angular net frequency $\omega_1$, in case of dynamic eccentricity is equal to $\omega_1 \pm \omega_r$, where $\omega_r$ is rotational speed. Therefore if magnetic flux density in any point of the air-gap is analysed with respect to time, only net frequency $f_1$ is observed under static eccentricity. Vice-versa in case of dynamic eccentricity the frequency components $f_1 \pm f_r$ arise.

Assuming serial connection of the stator winding, pure dynamic eccentricity doesn’t produce $f_1 \pm f_r$ components in stator currents. However, these components are present in the air-gap field and can be analysed.

Fig. 1. Rotor displacement under static and dynamic eccentricity
Although some works have been presented [7], realization of the measurement of magnetic flux density in the air-gap is difficult and doesn’t fully satisfy requirements on non-invasive diagnosis. Moreover, detection of dynamic eccentricity in stator current around the principal slot harmonic (PSH) is effective only for some combination of number of pole pairs and rotor slots [8].

III. METHOD DESCRIPTION

Essence of proposed method for detection of dynamic eccentricity is observation of external magnetic field from stationary position using a small active area sensor. The minimal air-gap length therefore rotates towards this observer and produces characteristic frequency components \( f_1 \pm f_r \) in measured signal like in any stationary point in the air-gap. To be precise, tangential component of the stray flux density is analysed. Advantage of this approach is efficient detection of dynamic eccentricity based on similar character of external magnetic field and air-gap field.

Analysis of external magnetic field, also known as flux signature analysis (FSA), isn’t as common as motor current signature analysis (MCSA), especially if the radial stray flux is taken into account. However several papers have been presented and have proved the usability of this approach. These papers are focused on diagnosis of broken rotor bar [9 – 15], stator cutting phase fault [9], stator winding short-circuits [10, 16], wound rotor phase disconnection [12], net voltage asymmetry [14], where the FSA shows the similar usability like MCSA. In case of dynamic eccentricity analysis authors usually refer to MCSA techniques.

The approach similar to that presented in this paper has been used for the rotor faults diagnosis of synchronous machines [17, 18].

IV. FEM ANALYSIS

As was mentioned above, the dynamic rotor eccentricity produces additional frequency components \( f_1 \pm f_r \) in the air-gap field and their amplitudes can be roughly calculated using air-gap permeance and Ampere’s Circuital Law. However, this calculation does not respect the real distribution of the magnetomotive force in the air-gap and nonlinear character of ferromagnetic material. The problem can be overcome using FE method.

The six poles, 200 W, squirrel-cage three-phase induction motor is used for the analysis of eccentricity impact on the external magnetic field under no-load operation. Waveforms of magnetic flux density are observed in two stationary points outside the machine and converted to the frequency domain via FFT. Both points are located 9 mm above the stator packet surface and the angular location of the first point is \( \theta = 0^\circ \), whereas the location of the second point is \( \theta = 180^\circ \) (see Fig.1). The analysis of external magnetic field is done for the several levels of static \( \varepsilon_s \) and dynamic \( \varepsilon_d \) eccentricity (0%, 5%, 15%, 30%) and their mutual combinations. Diagnostic signal is mainly affected by dynamic eccentricity, because the position of minimal air-gap length rotates relatively to the observing point and evokes the characteristic frequency components. Static eccentricity has only a limited influence and causes primarily deformation of spatial distribution of the magnetic field. The amplitudes of the characteristic frequency components presented in following figures are relative to the amplitude of the fundamental harmonic (100%) and the linear scale is used due to clarity.

Assuming mixed eccentricity, the spectrum is dependent on the observation point location and location of the minimal air-gap caused by static eccentricity. If the minimal air-gap caused by static eccentricity lies close to the observing point \( (\theta = 0^\circ) \), increasing level of static eccentricity causes decrease of mean gap length in this area. Therefore, the characteristic frequency components should increase, however this phenomenon always occurs only, if the magnetic material is linear. Considering the nonlinear material, the characteristic components are significantly affected by saturation of the stator yoke and their amplitudes may increase. The impact of material nonlinearity is the most significant if the saturation of surface layer of stator yoke is close to the “knee” on magnetising curve.

Fig. 2. Characteristic frequency components; \( \varepsilon_d = 5\% \), \( \theta = 0^\circ \)

Fig. 3. Characteristic frequency components; \( \varepsilon_d = 15\% \), \( \theta = 0^\circ \)
The mentioned phenomenon is presented in Fig. 2 and Fig. 3. The level of dynamic eccentricity is fixed of 5% and 15% respectively, while the static eccentricity increases from zero. For linear material (dashed line), the frequency components have slightly increased with increasing level of static eccentricity, however for nonlinear material these components have decreased (solid line). Comparing Fig.2 and Fig.3 is obvious that dynamic eccentricity has more significant influence to the characteristic frequencies than static eccentricity.

If the maximal air-gap caused by static eccentricity lies close to the observing point \((\theta = 180^\circ)\), increasing level of static eccentricity should ideally cause decrease of characteristic components, but the saturation has more significant influence (see Fig.4 and Fig.5) and the amplitude of these components have increased.

The material saturation effect is also examined separately for three magnitudes of the stator current \(I_m = 1\,\text{A}, 2\,\text{A}, 3\,\text{A}\). The frequency components of the magnetic flux density in the air gap for the motor with dynamic eccentricity of 15% and without static eccentricity are presented in Fig.6. Decreasing permeability of the magnetic circuit reduces the impact of non-uniform air-gap and therefore the characteristic components \(f_1 \pm f_r\) have decreased (solid line). However, the saturation of magnetic circuit has different impact on the flux density waveform outside the machine. Although described phenomenon in the air gap affects also external magnetic field, there is another one which can be more significant. The variation of the flux density in the air-gap evoked by eccentricity can cause the variation of permeability in stator yoke during rotor revolution and modify the condition on the boundary of iron and air. Therefore the saturation of surface layer of stator yoke works like an amplifier with variable gain whereas the maximal gain is around the “knee” of magnetising curve (Fig.6 – dashed line).

V. EXPERIMENTAL RESULTS

The measurement is carried out on three induction motors (IM1, IM2, IM3). These machines were delivered directly from a factory because some manufactured motors of this type generate unusual noise. The motor marked as IM2 was subjectively identified as faulty.

The measurement and analysis of external magnetic field of the surveyed machines were focused on a dynamic rotor eccentricity evaluation. Waveforms of the tangential component of the magnetic flux density were measured in observing point located 9 mm above the stator packet surface, similarly to FEM model. The axial location of the observing point is in the middle of the stator packet length. The measurement of the external magnetic field was done using a Hall probe and motor operating conditions correspond to the input values of the FEM model (no load, symmetrical three-phase voltage 230V / 50Hz).
The measured spectrum of the magnetic flux density outside the analysed machines are presented in Fig. 7. The experimental analysis of the external magnetic field for various combinations of stators (S1-S3) and faulty rotor R2 was also carried out and the results are presented in Fig. 8. It is clear that the most eccentric rotor R2 can be easily detected in all stators and the characteristic spectral lines are approximately the same in these cases. It shows good correlation with the calculated results.

The physical measurement of the rotor eccentricity was performed by a distance-drift meter due to the unknown real level of eccentricity. The real eccentricity of rotor R2 is nearly of 17% in relation to the nominal air gap length (0.2 mm). The level of the rotor eccentricity of induction motors IM1 and IM3 is similar and the eccentricity value is around of 5%.

VI. CONCLUSION

Described method allows to detect purely dynamic eccentricity or to detect dynamic eccentricity under mixed eccentricity with a minimal effect of static eccentricity. This feature can be understood as an advantage of this method, because the same frequency components \( f_1 \pm f_r \) are presented in stator current only if both types of eccentricity exist together and it is not easy to distinguish them. Drawback of the method is relatively significant impact of the stator yoke saturation.

Fig. 8. Measured spectrum of magnetic flux density Bₜ outside the machine, 9 mm above the stator packet surface. Several combinations of the faulty rotor R2 (ε=17%) and of the stators of IM1, IM2, IM3.

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REFERENCES


