FAULTS DETECTION OF INDUCTION MACHINES BY RADIAL FIELD MEASUREMENT

Driss Belkhayat — Raphaël Romary — Mustapha El Adnani — Rodolphe Corton — Jean François Brudny

In this paper, the authors propose a diagnosis method based on the measurement of the radial magnetic field in the surrounding area of an induction machine. Considering a star coupled induction machine, the effect of broken rotor bar fault or a stator phase cutting fault on stator currents and radial field spectrum is analyzed as an illustration of this diagnosis method. When the saturation is taken into account, the study shows that the fault causes the circulation of a third harmonic current between the two fed phases. This harmonic current generates new spectrum lines in the air gap flux density linked to the slotting effect. These high frequency components are easily detectable by the radial field measurement.

Keywords: Induction machine, diagnosis, radial magnetic field, slotting effect, flux density components

1 INTRODUCTION

In the recent few years much work has been carried out to investigate the possible fault operations of electrical machines. These works have used the acquisition of an experimental data set. Monitoring and diagnostics of electrical machines is a very important topic which corresponds to the actual industrial requests.

The usual methods for both stator and rotor fault detection are based on vibrations analysis [1] or on the motor current signature analysis [2] that originated more than twenty years ago.

For this purpose, these methods need dedicated and fixed equipment for each induction machine under test. In the mean time, a new non-invasive technique is proposed. This new method consists in using a voltage sensor based on an air coil antenna installed outside the machine. This antenna measures the voltage proportional to the emitted magnetic field.

The technique using the measurement of the axial leakage flux, by setting the antenna in the axis of the shaft, has been widely developed [3].

In this investigation the external coil is placed in a plant containing the axis of the machine (Fig. 1). The electric field intensity sensed by the antenna is so proportional to the radial magnetic field. Its spectrum analysis shows high frequency components (MHz) due to the fast front waves voltage when the machine is supplied by a PWM inverter [4], [5]. The mean frequency components (kHz) are due to the slotting effect [6] and appear, even if the machine is safe and supplied by the network [7]. The interference of these components by the fault field harmonics is used to diagnose the machine behaviour.

This technique is very practical and can be implemented at low cost, except for very small motors, because the antenna can be removed from one machine to another without stopping work.

2 HEALTHY MACHINE

2.1 Magnetic field components

This analytical study is based on the determination of the air gap flux density expression where the saturation is neglected. The principle of this determination has been presented in previous publications [8], [9]. Only the main results are presented in this paper.

A three phase, $p$-pole pairs squirrel cage induction machine with single layer windings and all the conductors series connected is considered. Using an idealized slot model with a rectangular profile and taking into account the teeth, the general expression of the air gap permeance is

$$ p = P_0 + p_{teeth} $$

where $P_0$ is the mean value of permeance. In a healthy running, this relationship can be written as [8]

$$ p = \sum_{k^s=-\infty}^{\infty} \sum_{k^r=-\infty}^{\infty} P_{k^s k^r} \cos((k^s N^s + k^r N^r) \rho \alpha - k^r N^r \rho \theta) $$

where are

* Laboratoire Systèmes Electrotechniques et Environnement, Université d’Artois, Faculté des Sciences Appliquées, Technoparc Futura, 62400 Béthune, France

** Faculté des Sciences et Techniques, Département de physique, Marrakech, Morocco, e-mail : belkhayat@fstg-marrakech.ac.ma

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positive, negative or null integer
N\textsuperscript{s}, N\textsuperscript{r} — stator and rotor slot number per pair pole
p — pair pole number
\alpha\textsuperscript{s} — angular position of any point in the air-gap
\theta — angle between rotor phase 1 and stator phase 1 taken as spatial reference
P_{k\textsuperscript{r}k\textsuperscript{r}} — coefficient linked to magnetic circuit geometry

In order to distinguish the stator and rotor quantities, the upper indexes \( s \) and \( r \) are used.

Considering a balanced sine current three phase system at frequency \( f (\omega \text{ angular frequency}) \) flowing through the stator windings and the following relationship giving the magnetic field intensity \( \varepsilon^s \) created by the stator

\[
\varepsilon^s = \sum_{q=1}^{3} i_q^s \sum_{k^s=1}^{+\infty} \sum_{k^r=1}^{+\infty} \sum_{k^r=-\infty}^{+\infty} A_{k^s}^s \cos \left( \left( p \alpha^s - (q-1) \frac{2\pi}{3} \right) \right) \tag{3}
\]

where
\( i_q^s \) — phase “\( q \)” stator current (\( q = 1, 2 \) or 3)
\( h^s \) — rank of harmonic component
\( A_{k^r}^s \) — coefficient linked to the winding

The radial air gap flux density components created by the stator are obtained by multiplying the relations (2) and (3)

\[
b^s = \sum_{q=1}^{3} \sum_{k^s=1}^{+\infty} \sum_{k^r=1}^{+\infty} \sum_{k^r=-\infty}^{+\infty} A_{k^s}^s P_{k^r k^s} \cos \left( \left( h^s + k^s N^s + k^r N^r \right) \right) \omega t - (h^s + k^s N^s + k^r N^r) \rho \theta_0 \tag{4}
\]

Noting \( s \) the slip and \( I^s \) the RMS value of \( i_q^s \), as \( \theta = \theta_0 + (1 - s) \omega t / p \) the relationship (4) becomes

\[
b^s = \frac{3}{2} I^s \sqrt{2} \sum_{h^s=1}^{+\infty} \sum_{k^r=1}^{+\infty} \sum_{k^r=-\infty}^{+\infty} A_{h^s}^s P_{k^r k^s} \cos \left( \left( 1 + k^r N^r \right) \right) \omega t - (h^s + k^s N^s + k^r N^r) \rho \theta_0 \tag{5}
\]

where \( h^s = 6k^s + 1 \) (\( k^s \) is positive, negative or null integer)

In this expression it can be clearly shown that harmonics at \( \omega + (1 - s) \omega k^s N^r \) angular frequencies will appear in the air gap flux density spectrum.

Noting \( \alpha^s = \alpha^r + \theta \), where \( \alpha^r \) is the angular position of any point in the air gap relating to the rotor referential, the air gap flux density linked to this rotor referential can be written as

\[
b^r = \frac{3}{2} I^r \sqrt{2} \sum_{h^r=1}^{+\infty} \sum_{k^r=1}^{+\infty} \sum_{k^r=-\infty}^{+\infty} A_{h^r}^r P_{k^r k^s} \cos \left( \left( 1 + k^r N^r \right) \right) \omega t - (h^s + k^s N^s + k^r N^r) \rho \theta_0 \tag{6}
\]

The prime is introduced for quantities which are expressed in a different referential.

These flux density components induce rotor current harmonics which will be at the origin of rotor flux density components. In order to show the main effect, only the terms obtained for \( h^s = 1 \), corresponding to the rotor current harmonics at \( \left( 1 + k^s N^s \right) \omega \) pulsation, will be considered. These harmonics generate magnetic field intensity given by

\[
\varepsilon^r = \sum_{h^r=1}^{+\infty} \sum_{k^r=1}^{+\infty} \sum_{k^r=-\infty}^{+\infty} \hat{\varepsilon}_{k^r} \cos \left( \left( 1 + k^s N^s \right) \omega t - ph^r \alpha^r - \phi_{k^r}^r \right) \tag{7}
\]

where \( \phi_{k^r}^r \) is the rotor current phase lag related to \( k^r \).
This magnetic field intensity combined with the permeance term \( P_0 \), create a rotating field which can be expressed by

\[
b^r = \sum_{h^r=1}^{+\infty} \sum_{k^r=1}^{+\infty} \sum_{k^r=-\infty}^{+\infty} \hat{b}_{k^r}^r \cos \left( \left( 1 + k^s N^s \right) \omega t - ph^r \alpha^r - \phi_{k^r}^r \right) \tag{8}
\]

Other terms are induced by \( P_{k^r k^s} \) but are neglected in order to simplify the presentation. For \( h^r = 1 \), this flux density expression, relating to the stator, can be written as

\[
b^r = \sum_{k^r=-\infty}^{+\infty} \hat{b}_{k^r}^r \cos \left( \left( 1 - k^s N^s \right) \omega t - ph^r \alpha^r + \rho \theta_0 - \phi_{k^r}^r \right) \tag{9}
\]

This relationship shows that air gap flux density harmonics at \( \left( 1 + k^s N^s \right) \omega \) angular frequencies will appear in the spectrum. In normal running (\( s \approx 0 \)), these harmonics will be at \( \left( 1 + k^s N^s \right) \omega \) angular frequencies.

2.2 Experimental tests

The experimental results concern a 3 kW, 400/230 V, 50 Hz, 2-poles pairs, squirrel cage induction machine with 36 slots in the stator \( (N^s = 18) \) and 44 slots in the rotor \( (N^r = 22) \). In Fig. 1 we can see the real experimental system with an antenna having a pass-band at 10 MHz. In order to avoid the field produced by the power system, the position of the antenna is carefully chosen to measure only the radial magnetic field emitted by the working machine.

For the following study, the experimental tests and results are presented for the same machine.

In the spectrum presented in Fig. 1 we can clearly distinguish the mains flux density components \( b^s \) created by the stator and given by the relationship (5) and those ones created by the rotor and given by the relationship (9). The magnitudes of the spectrum lines are given in volts. The corresponding values in tesla can be easily obtained using the constructor characteristic curve of the antenna.
3 MACHINE FAULTS

3.1 Broken rotor bar fault

Broken rotor bar is one of the most frequent faults studied on the squirrel-cage induction motor [10], [11]. This type of failure does not cause motor destruction immediately. The machine performances do not decrease, but it has been shown [12] that the current increases in the adjacent bars to the broken one. This anomaly can induce additional heating which leads to supplementary failures. Other studies [13], [14] prove that the broken bar fault can be detected by observing the stator current spectrum where an additional line appears at \((1 - 2s)f\) frequency. This spectrum line is not easy to detect because it is close to the fundamental current at \(f\) frequency. So, a higher frequency band, containing the slot harmonics, is observed to detect the effects of the broken bar fault.

Modification of the rotor mmf

The failure leads to a gap in the rotor mmf wave at the broken bar position. It can be shown that this gap can be modelled by introducing a ratio \(R\), function of \(\alpha'\), between the modified mmf \(f'\) and the initial mmf \(e'\) given by (7).

\[
f' = R(\alpha')e'. \tag{10}
\]

This ratio \(R\) can be decomposed into Fourier series as

\[
R(\alpha') = 1 + \sum_{h' = 1}^{+\infty} R_{h'} \cos(h' \alpha'). \tag{11}
\]

In order to show the preponderant effects of the broken bar, only the first term of the Fourier series will be considered (\(h' = 1\))

\[
R(\alpha') = 1 + R_1 \cos \alpha'. \tag{12}
\]

Equations (10) and (12) show that an additional term \(R_1 e' \cos \alpha'\) appears. The main term of the corresponding flux density, taking only \(P_0\) into account, is given by

\[
B_r^0 = P_0 R e'.
\]

The development leads to

\[
B_r^0 = \sum_{k = -\infty}^{+\infty} \hat{B}_{k+1} \cos \left( (1 - k^0 N^0)(1 - s) \right) \omega t - (p \pm 1) \alpha' = \varphi_{k+1} \tag{13}
\]

with \(\hat{B}_{k+1} = P_0 \delta_{k+1} R_1\).

Relating to the stator referential, it comes

\[
B_u^r = \sum_{k = -\infty}^{+\infty} \hat{B}_{k+1} \cos \left( (1 - k^0 N^0(1 - s)) \omega t \pm (1 - s) \frac{\omega t}{p} \right) - \alpha'(p \pm 1) - (p \pm 1) \theta_0 - \varphi_{k+1} \tag{14}
\]

The comparison between (14) and (9) shows off additional harmonics at \(\pm \omega_R\) from the initial ones. For \(N^0 = 18\), the frequencies of components relative to \(|ks| = 1\) (ranks 17 and 19) are nearly at 850 Hz and 950 Hz. For \(|ks| = 2\) the frequencies are close to 1750 Hz and 1850 Hz. The broken bar fault brings spectrum lines at 825 Hz, 875 Hz, 925 Hz, 975 Hz (\(|k^s| = 1\)) and 1725 Hz, 1775 Hz, 1825 Hz, 1875 Hz (\(|k^s| = 2\).
Experimental verifications.

The upper spectrum given in Fig. 2 corresponds to a healthy running (see Fig. 1). The lower spectrum corresponds to a broken bar fault. The results give good confirmation of the analytical predictions. In the tests the rotation speed is practically at synchronism. Lateral spectrum lines in the case of broken bar can be observed. These lines can be easily detected and their frequencies are at \( \pm f_R \) from the initial harmonics corresponding to the teeth effect in a healthy running. It can be noticed that this phenomenon also appears on the spectral lines generated by the stator currents (\(|k^r| = 1\) 1050 Hz, 1150 Hz).

3.2 Stator Cutting phase fault

In order to justify the phenomena in case of stator cutting phase, the saturation has also to be taken into account, so that the expression (4) becomes

\[
p = P_0 + P_{\text{teeth}} + p_{\text{sat}}.
\]  

(15)

Saturation effect

It is known that the saturation effect increases the air-gap equivalent thickness and consequently decreases the permeance [15], [16]. The permeance saturation term is given by

\[
p_{\text{sat}} = \hat{P}_{\text{sat}} \cos(2\omega t - 2p\alpha^s).
\]  

(16)

The permeance expression is linked to the maximum of magnetic field intensity which is at the origin of the saturation. In order to appreciate the main corresponding effects, only the magnetic field intensity fundamental term is considered.

- **Balanced Three phase supply**

In that case, after multiplying (16) and the magnetic field intensity (3), the following supplementary term appears in the air gap flux density expression

\[
b_{\text{sat}}^s = \frac{3}{4} A_1^s \hat{P}_{\text{sat}} I^s \cos(3\omega t - 3p\alpha^s).
\]  

(17)

Integration of this term leads to a supplementary linked flux through the stator phase “q” \( \hat{\varphi}^q_3 \cos 3\omega t \) and therefore induces a zero-sequence electric field intensity system. In the case of machine star coupling without neutral, it is evident that there will not appear any corresponding current flowing.

- **Two phase supply**

In that case, let us consider the previous current system with \( i_{\text{sat}}^s = -i_{\text{sat}}^s = I^s \sqrt{2} \cos \omega t \) and \( i_1^s = 0 \). The magnetic field intensity becomes a pulsating wave instead of a rotating one. The maximum of the magnetic field intensity is always located at the same points

\[
e^s = A_1^s I^s \sqrt{2} \cos(\omega t) \cos(p\alpha^s + \frac{\pi}{6}).
\]  

(18)

The saturation permeance term can be written as

\[
p_{\text{sat}} = \hat{P}_{\text{sat}} \cos 2\omega t \cos(2p\alpha^s + \frac{\pi}{3}).
\]  

(19)

The product of (18) and (19) leads to several terms and a particular one

\[
b_{\text{sat}}^s = \sqrt{6} A_1^s \hat{P}_{\text{sat}} \cos(3\omega t - p\alpha^s).
\]  

(20)

After integration, the flux linked to “q” stator phase is

\[
\varphi_{\text{sat},s}^q = \hat{\varphi}_{\text{sat}} \cos(3\omega t - (q - 1)\frac{2\pi}{3}).
\]  

(21)

This flux induces a third harmonic of electric field intensity with RMS value \( E_{\text{sat},s}^s = 3\omega \hat{\varphi}_{\text{sat}} / \sqrt{2} \) and therefore, the third harmonic current component can flow through the two fed phases. This current is limited by the machine and grid impedance \( Z \) for the third harmonic current (Fig. 3).

![Fig. 3. Equivalent scheme for the third harmonic current component](image_url)

To confirm this property, experiments have been made on a 1.5 kW 400/230 V 50 Hz, 2 pole pair induction machine with \( N^\ast = 18 \) and \( N^r = 12 \).

In the obtained spectra given in Fig. 4, the observation of the third harmonic component in the field measured by the antenna does not allow to appreciate the unconnected phase fault because it is approximately the same in the both cases. However, it can be easily noticed that the corresponding current harmonic appears clearly. The low magnitude original component at 150 Hz figuring in the three phase supply current spectrum is not due to the zero-sequence electric field intensity system as emphasized in the analytical development. It corresponds to the third harmonic of the supply system.
Interaction with the teeth effect

In the case of one stator phase cut and considering third harmonic of the current, the development of the relationship (4) leads to obtain stator field components at \[ k''N'(1-s)\omega \pm 3\omega \] angular frequencies which are corresponding to the interaction of third harmonic current with the rotor slots. The experiments show that these harmonics (Fig. 5) appearing clearly in the lower spectrum (2 phase supply), for \( s \geq 0 \) additional spectral lines at 900 ± 150 Hz \( (k'' = 1) \), 1800 ± 150 Hz \( (k'' = 2) \) and 2700 ± 150 Hz \( (k'' = 3) \) appear. Therefore this technique gives a good appreciation on the machine diagnosis concerning a stator phase cutting fault.

4 CONCLUSION

In this paper, the authors have presented a new diagnosis method consisting in the use of an antenna positioned in the surrounding area of the induction machine for the measurement of the radial magnetic field. It has been shown that the spectrum of this field contains high rank lines due to the slotting effect giving information concerning broken rotor bar and stator cutting phase machine faults. This result is particularly important to discriminate the induction machine faults from the power system fault. So, the proposed approach is very interesting for manufacturers to detect machines faults without any mechanical link and using low cost non-invasive sensor. Other studies are now undertaken to extract more information from the magnetic field emitted in view to identify other machine faults.

REFERENCES

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