On-line monitoring and diagnosis of broken rotor bars in induction motor

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Abstract

The monitoring and the diagnosis of the defects in induction motors starting from the stator current are very interesting, since it is an accessible and measurable quantity. The spectral analysis of the stator current makes it possible to highlight the characteristic frequencies of the defects but in a wide frequency range depending on half the sampling frequency, making it very difficult to monitor on-line the defects. In order to facilitate the use of the relevant frequencies of the breaking-bar defect we proposed the extraction of the frequency components using two methods, namely, the amplitude and the instantaneous frequency. The theoretical bases of these methods were presented and the results were validated on a test bench with an induction motor of 5.5 kw.

1. Introduction

Induction machines are increasingly used in electric drives. This machine, in the last three decades, has been the subject of several research works directed primarily towards the design of control laws ever more efficient. Its multiple qualities: low cost, robustness and performances make it a special familiar machine in industrial environment. The requirements of reliability and productivity of installations require the integration of a system of monitoring and diagnosis of failures. It must be necessary, therefore, to provide the motors with some tools for monitoring and diagnosis of faults, thus we will be able to avoid and prevent the breakdowns and the spurious shutdowns.

The techniques and methods for monitoring and diagnosis treated in the literature [1-6] based on monitoring the temporal evolution and/or the spectral content of the signal. Most are based on direct analysis of the spectrum of the measured variable. They allow to extract a particular frequency (demodulation, filtering), a frequency band (filtering, FFT). It is about methods known as MCSA (Motor Current Signature Analysis) methods. Signal processing, particularly the spectral analysis of vibration or electrical signals, is frequently used to detect faults in electric machines, in particular the defect of rotor breaking bars, stator faults and bearings defects. This method is particularly suited to this type of defects since these latter emerge by the appearance of certain frequencies, directly related to the speed of the machine and the frequency of the power supply. The methods of spectral analysis are used on electrical stationary quantities when the electrical machine is connected to the network or to a frequency converter. The case of non-stationarity has also been used in the method of the disconnection of power to the motor [7], where the spectrum of the residual emf in the stator windings is used for the detection of rotor and stator faults. Monitoring of characteristic frequencies allow the characterization of many defects in the induction machine and this, sometimes independently of the amplitude of the measured signals (the occurrence or the modification of a characteristic frequency determines the presence of the defect and not the amplitude of the measured signal). On-line monitoring of defects through the spectral analysis is not an easy task because of the presence of all the frequency components included in the signal especially the fundamental that may sometimes inhibit the default characteristic components at low spectral resolution. The techniques of the amplitude and instantaneous frequency can overcome these problems and allow a better extraction and exploitation of the frequency component specific to the failure.

2. Detectıon of defects by ınstantaneous amplıtude

The current in a stator phase of an electric motor can be developed in Fourier series:

$$i_a(t) = \sum_k \sqrt{2} I_{ak} \sin(k\omega t + \varphi_{ak}) \quad (1)$$

Note that k_M represents the order of the harmonic with the maximum frequency after filtering of the current $i_a(t)$

$$i_a(m) = \sum_{k=1}^{k_M} \sqrt{2} I_{ak} \sin(k\omega m\Delta t + \varphi_{ak}) \quad (2)$$

Where k is a real positive representing the range of harmonic components.

$I_{ak}, k\omega, \varphi_{ak}$ are, Effective (rms), angular frequency and phase angle of the k^{th} harmonic respectively. Each harmonic $i_a(t)$ can be represented by the harmonic phaser.

$$I_{ak} = I_{ak} \exp(j\varphi_{ak}) \quad (3)$$

Given a real signal, in this case the stator phase current of the expression (3), the instantaneous amplitude is the module of the Hilbert transform of the considered signal. Since the signal is broadband and contains harmonics from various sources (source pollution or harmonics induced by the machine itself), we will remove the unwanted harmonics by filtering the current signal by a low pass filter with a cut off frequency of 100 Hz. The principle of the instantaneous amplitude is illustrated in Fig. 1

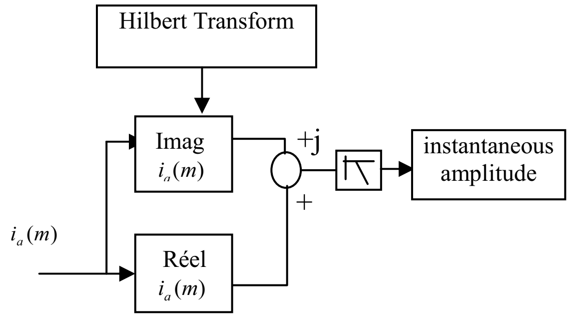

Fig. 1. Principle of instantaneous amplitude.

3. Detectıon of defects by the ınstantaneous frequency

The technique of instantaneous amplitude facilitates the detection of the failure that appears as in the form of the instantaneous amplitude modulation independently of the frequency and the phase. The detection of the characteristic frequency is often sufficient to detect the presence of the default without regard to its amplitude. The instantaneous frequency allows the monitoring of the characteristic frequency of the defect. Its principle is based on the decomposition of the signal into its symmetrical direct and inverse components in addition to the determination of the instantaneous frequency. This technique will be applied to the phase current of the motor powered by the power supply network or by inverter.

According to Fortescue [8], a three-phase system represented by a harmonic phaser ($\bar{i}_{ah}, \bar{i}_{bh}, \bar{i}_{ch}$) can be decomposed into two balanced systems of harmonic phasers: one of a direct sequence ($\bar{i}_{pk}, a^2\bar{i}_{pk}, a\bar{i}_{pk}$), and the other of a reverse sequence ($\bar{i}_{nk}, a\bar{i}_{nk}, a^2\bar{i}_{nk}$).

The operator $a = \exp(j2\pi/3)$ defines a rotation of $2\pi/3$ in the anticlockwise direction.

The harmonic phasers $\bar{i}_{pk}$ and $\bar{i}_{nk}$ are symmetrical harmonic components of positive and negative sequence respectively. They are described as follows:

$$\bar{i}_{pk} = \frac{1}{3}\left(\bar{i}_{ah} + a\bar{i}_{bh} + a^2\bar{i}_{ch}\right) \tag{4}$$

$$\bar{i}_{nk} = \frac{1}{3}\left(\bar{i}_{ah} + a^2\bar{i}_{bh} + a\bar{i}_{ch}\right) \tag{5}$$

Lyon [9] introduced the instantaneous symmetrical component to predict the transient behaviour of the electrical machine. The instantaneous symmetrical component (scalar) of direct sequence is given by:

$$i_p(t) = \frac{\sqrt{2}}{3}\left(i_a(t) + a i_b(t) + a^2 i_c(t)\right) \tag{6}$$

In the above equation, the coefficient $\sqrt{2}/3$ was introduced for the convenience of calculation in place of the original coefficient 1/3, proposed by Lyon [9]. The instantaneous symmetrical component of reverse sequence is the complex conjugate of the instantaneous symmetrical component of direct sequence, it is given by:

$$i_n(t) = \frac{\sqrt{2}}{3}\left(i_a(t) + a^2 i_b(t) + a i_c(t)\right) \tag{7}$$

The relationship between the instantaneous symmetrical component of direct sequence and the symmetrical harmonic components is defined by [10]:

$$\operatorname{Re} i_p(t) = -\frac{j}{2}\sum_k \left(i_{pk} + i_{nk}\right)\exp(jk\omega t) + \frac{j}{2}\sum_k \left(i_{pk}^* + i_{nk}^*\right)\exp(-jk\omega t) \tag{8}$$

$$\operatorname{Im} i_p(t) = -\frac{1}{2}\sum_k \left(i_{pk} - i_{nk}\right)\exp(jk\omega t) - \frac{1}{2}\sum_k \left(i_{pk}^* - i_{nk}^*\right)\exp(-jk\omega t) \tag{9}$$

The asterisk (*) defines the complex conjugate. However we can write:

$$i_p(t) = -j\sum_k i_{pk}\exp(jk\omega t) + j\sum_k i_{nk}^*\exp(-jk\omega t) \qquad 10)$$

The instantaneous symmetrical component of direct sequence defined in equation (10) can be measured at a regular interval of time Δt through an A/D converter having at least two channels of data acquisition for two currents from which we extrapolate the third current. In fact, it is sufficient to acquire samples of two currents to calculate [10]:

$$\operatorname{Re} i_p(m) = \sqrt{\frac{2}{3}}\, i_a(m\Delta t) - \frac{1}{\sqrt{6}} i_b(m\Delta t) - \frac{1}{\sqrt{6}} i_c(m\Delta t) \tag{11}$$

$$\operatorname{Im} i_p(m) = \frac{1}{\sqrt{2}} i_b(m\Delta t) - \frac{1}{\sqrt{2}} i_c(m\Delta t) \tag{12}$$

$$m = 0,1,2...$$

Note that the measured signals are filtered in order to avoid the problem of aliasing. Designating by k_m the rank of the harmonic with the maximum frequency after filtering, equation (10) takes the following discrete form:

$$i_p(m) = -j\sum_{k=1}^{k_M} i_{pk}\exp(jk\omega m\Delta t) + j\sum_{k=1}^{k_M} i_{nk}^*\exp(-jk\omega m\Delta t) \tag{13}$$

The instantaneous frequency $f(t)$ uses the notion of the signal instantaneous phase, it is defined as the derivative of the phase $\varphi(t)$ (Fig. 2).

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \quad (14)$$

With *f* in Hertz

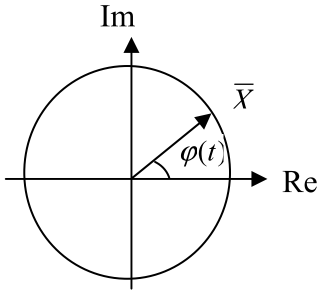

Fig. 2. Vector representation.

Consider a real signal $x(t)$, we obtain the phase $\varphi(t)$ from the associated signal $y(t)$ in quadrature. This latter is determined by the Hilbert transform

$$y(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(t)}{t-\tau}d\tau \quad (15)$$

Which, from the real signal, provides the complex form:

$$x(t) + j\,y(t)$$

The phase φ is the arctangent between y (t) et x(t).

$$f_i = \frac{1}{2\pi}\frac{d}{dt}\arctan\left(\frac{y}{x}\right) = \frac{1}{2\pi}\frac{xy' - yx'}{x^2 + y^2} \quad (16)$$

With $x' = dx/dt$ et $y' = dy/dt$

The current instantaneous symmetrical component, allows us to directly have two quantities in quadrature of phase which are the real and imaginary components of the current vector $i(t)$. If the currents are sampled periodically so that the angle between two sampling instants $\Delta\varphi$ is small (Fig. 3), we can obtained in this case the instantaneous frequency of the instantaneous symmetrical component of positive sequence [11].

$$\Delta\varphi \cong \sin(\varphi_m - \varphi_{m-1}) \quad (17)$$

$$\Delta\varphi \cong \sin\varphi_m \cos\varphi_{m-1} - \sin\varphi_{m-1}\cos\varphi_m \quad (18)$$

According to equations (11) and (12) we can write for a balanced three-phase system:

$$\mathrm{Re}\, i_p(m) = i_m \cos(\varphi_m) \quad (19)$$

$$\mathrm{Im}\, i_p(m) = i_m \sin(\varphi_m) \quad (20)$$

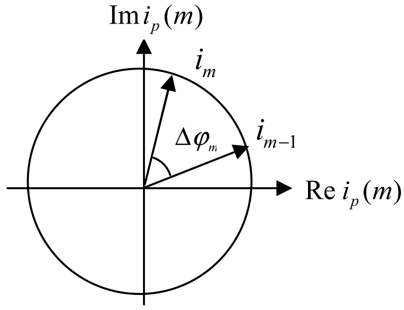

Fig. 3. Vector representation of the instantaneous vector

The instantaneous symmetrical component along the axis α and β can be written:

$$i_{\alpha m} = \mathrm{Re}\, i_p(m) \quad (21)$$

$$i_{\beta m} = \mathrm{Im}\, i_p(m) \quad (22)$$

$$i_m = \sqrt{i_{\alpha m}^2 + i_{\beta m}^2} \quad (23)$$

since

$$f_i = \frac{1}{2\pi}\frac{d}{dt}(\varphi) \quad (24)$$

Yields:

$$f_i = \frac{1}{2\pi T}\frac{1}{i_m i_{m-1}}\left(i_{\beta m} i_{\alpha m-1} - i_{\beta m-1} i_{\alpha m})\right) \quad (25)$$

Where *T* is the period

In practice, the current given by equations (11) and (12) are registered. The instantaneous symmetrical components along axes α and β are evaluated. Hence, the instantaneous frequency is derived.

4. Experimental results

The bench consists of a 5.5 kW three-phase squirrel cage induction motor. The motor is Leroy Somer LS 132S, IP 55, class F, T°C standardized = 40°C. The nominal voltage between phases: 400 V, the frequency of power supply 50 Hz, nominal speed 1440 tr/min, the number of the rotor slots Nr = 28. The number of stator slots Ns = 48. The stator windings are coupled in star. The motor is loaded by a powder brake. Its maximum torque (100 Nm) is reached at the nominal speed.

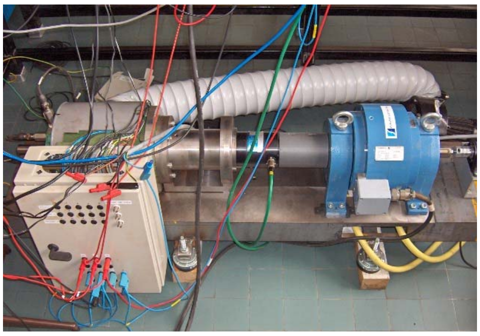

Fig. 4. Test bench

Fig. 5. Breaking of the rotor bars.

4.1. Results of the instantaneous amplitude

This technique is applied to a stator current (Fig. 6) of the induction motor supplied by an inverter. This machine, in this case presents a default of three broken rotor bars. Fig. 7 shows the instantaneous amplitudes of two currents one for a healthy case (dashed line) and the other for the case with fault (solid line). It shows that the instantaneous amplitude takes into account the oscillating part of period 1/2gf, owner of the interesting information. In addition, the fundamental component is eliminated, making the shape of the instantaneous amplitude more readable. The spectrum of the instantaneous amplitude (Fig. 8) illustrates the representative component of the defect, namely, in this example the breaking of three rotor bars of frequency 11 Hz.

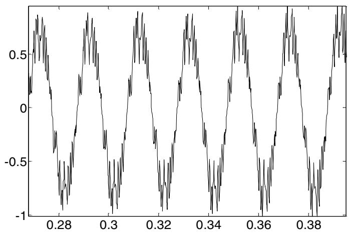

Fig. 6. Stator current of a motor powered by inverter with the defect of three broken rotor bars.

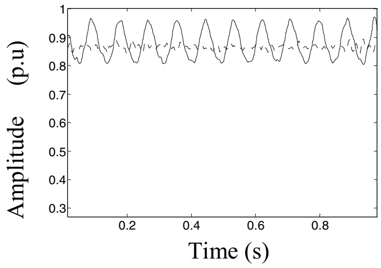

Fig. 7. Instantaneous amplitude of the stator current with three broken bars (solid line) and healthy current (dashed).

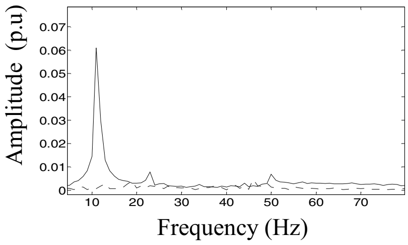

Fig. 8. Spectrum of its instantaneous amplitude. Three broken bars (solid line), healthy current (dashed)

4.2. Results of instantaneous frequency

The instantaneous frequency is applied to the stator current of the induction motor supplied by inverter. The stator currents of the machine have been bought up in charge and during continuous operation in two cases: healthy motor and motor with broken rotor bars. Fig. 9 shows the case of inverter supplied healthy machine: there is a strong deformation of the stator current that generated as a consequence a very large fluctuation of the instantaneous frequency that varies between -500 and 500 Hz. Consequently, we cannot characterize the operation of the healthy machine and obviously the defective one. The stator current has a very wide frequency range, which varies depending on the sampling frequency, in our case from 0 to 10,000 Hz.

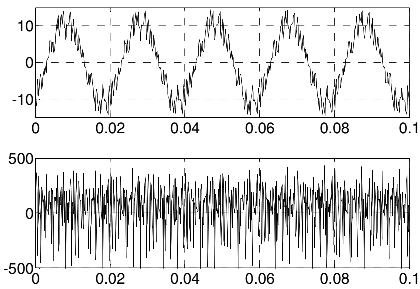

Fig. 9. Phase current and instantaneous frequency of a healthy motor supplied by inverter.

All existing frequencies in the currents contribute simultaneously to the instantaneous frequency, which makes it difficult to characterize or even to extract of a relevant signature. Note that the interesting frequencies have low values for both cases: healthy or defective. The fundamental frequency f=50Hz characterizes the healthy functioning, the frequency 2gf (g, slippage) characterizes the envelope of the defect of broken rotor bars. However, the initial frequency range can be reduced around the relevant frequencies in this case 160Hz.

Fig. 10 shows the instantaneous frequency of a stator current phase of the healthy motor supplied by inverter. The strong deformation of the stator current (red line) was attenuated by the reduction of the frequency range up to 160 Hz (black line) and which generated as a consequence an attenuation in the instantaneous frequency fluctuation. Note that despite the very reduced modulation around 50Hz, the instantaneous frequency of the phase current may, however, characterize a healthy functioning of the machine.

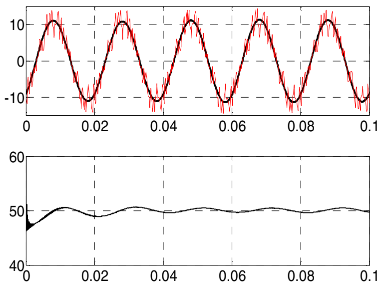

Fig. 10. Phase current and instantaneous frequency of a healthy motor supplied with an inverter (frequency band of 160 Hz).

Fig. 11 shows the instantaneous frequency of a stator current phase in the case of inverter supply of the machine with a defect of four broken bars. It is noted that the modulation of the stator current amplitude appears also as a form of equidistant envelopes of period *1/2gf* of 0.3 second and a maximum frequency of 52 Hz.

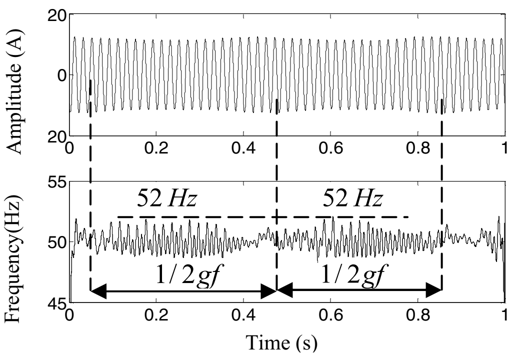

Fig. 11. Instantaneous frequency of a motor phase supplied with an inverter with 04 broken bars.

5. Conclusions

The stator current represents a data recording medium very rich in information. The traditional spectral analysis of the defect of broken bars does not allow better exploitation of the current signal because of the proximity of the characteristic components of the defect, some Hertz, to the dominant fundamental component at 50 Hz. The representation of one part of the signal: the instantaneous frequency or the instantaneous amplitude makes it possible to withdraw the fundamental one and maintain only the relevant information, in fact, the instantaneous amplitude and frequency. These have the advantage of being applied for an on-line monitoring and a diagnosis without being masked by the fundamental of the stator current.

6. References

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