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DETECTION IMPROVEMENT OF THE BROKEN ROTOR BARS OF IM AFTER SUPPLY DISCONNECTION

Abdesselam Lebaroud * — **Amar Bentounsi** **

This paper presents some analysis techniques of the voltages induced in the stator windings after supply disconnection, to detect broken rotor bars in induction motor (IM). When the motor is disconnected from the supply voltage, the broken bars cause a distortion of the magnetomotive force generated by rotor windings, and some particular harmonics induced in the stator windings increase their amplitude. The diagnostic technique is based on monitoring these voltage harmonics via the non parametric estimation of the modified periodogram and averaged periodogram. These techniques permit to evidence the principal harmonic frequencies of the signal and decrease the noise influence, thus allowing a better detection of the broken rotor bars.

K e y w o r d s: induction motor, detection, supply disconnection, broken bars

1 INTRODUCTION

The studies of induction motor behaviour during abnormal conditions and the possibility to diagnose these conditions have been a challenging topic for many electrical machine researchers. The major faults of electrical machines can broadly be classified as the following [1]

- Stator faults resulting in the opening or shorting of one or more of a stator phase windings,
- Abnormal connection of the stator windings,
- Broken rotor bar or cracked rotor end-rings.
- Static and/or dynamic air-gap irregularities,
- Bent shaft (akin to dynamic eccentricity) which can result in a rub between the rotor and stator, causing serious damage to stator core and windings.

These faults produce one or more of the symptoms as given below:

- Unbalanced air-gap voltages and line currents
- Increased torque pulsations,
- Decreased average torque,
- Increased losses and reduction in efficiency,
- Excessive heating.

In recent years, intensive research [2-8] effort has been focused on the technique of monitoring nd diagnosis of electrical machines and can be summarized as follows,

- Time and frequency domain analysis of induced voltages in search coils placed internally around stator tooth tip and yoke.
- Time and frequency domain analysis of shaft flux or more generally axial leakage flux which is monitored by using an external search coil wound around the shaft of a machine.
- Time domain analysis of the electromagnetic torque and flux phasor
- Temperature measurement, infrared recognition, radio frequency (RF) emission monitoring,
- Motor current signature analysis (MCSA)
- Detection by space vector angular fluctuation (SVAF)
- Noise and vibration monitoring,
- Chemical analysis,
- Acoustic noise measurements,
- Harmonic analysis of motor torque and speed,
- Model, artificial intelligence and neural network based techniques.

Of all the above techniques, MCSA is the best possible option: it is non-intrusive and uses the stator winding as the search coil; It is not affected by the type of load and other asymmetries [2], but this technique presents some difficulties because of the sensitivity of the stator current in particular to the saturation and the motor geometry which often presents asymmetries in stator or rotor. All these factors may lead to errors in fault detection. But the increasing interest for the MCSA is due to both the practical importance of this issue and the increasing availability of advanced hardware and software tools for signal processing. Therefore some researchers [914] have investigated the monitoring of machine conditions mainly based on the signature of external variables, for instance by means of all voltage and current signals, speed, torque and instantaneous power. They can be computed and more information may be retrieved for diagnostic purpose.

Broken rotor bars do not initially cause an IM to fail, but they can impair motor performance, lead to motor malfunction, and cause serious mechanical damage to the stator windings if left undetected [15]. Several diagnostic techniques have been proposed in the past to detect faults due to broken rotor bars. Most of them are based

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on the steady-state analysis of stator voltages and currents via fast Fourier transform (FFT) . A limit of this method is its dependence of the load: when this one is weak, the sidebands are too close to the fundamental frequency so that it is difficult to distinguish them. In order to improves the detectability of broken bars, the authors in [16] have compared the MUSIC and FFT algorithms to show that the MUSIC algorithm allows to reduce the noise influence and to give a better interpretation of the principal harmonics when the number of samples of the analyzed signal is small, or the window size is short. The authors of [16] use the FFT algorithm to detect the broken bars and have to look at a short-time window after supply disconnection so as to consider the signal to be quasi-stationary. In fact the induced stator voltage amplitude and frequency decrease rapidly due to the rotor current attenuation and the rotor slowing down. In this paper, an improvement of the periodogram is proposed, to analyze the voltages induced in the stator after supply disconnection. The analysis is conducted on one stator voltage phase. This method allows us to identify harmonics due to the faults in a simpler manner. Experimental results are reported to show the effectiveness of the proposed diagnostic technique.

2 MODIFIED PERIODOGRAM APPLIED TO STATOR VOLTAGE PHASE

A. Modified periodogram

The windowing of signals prior to computing the FFT is called a modified periodogram. This has the effect of reducing the height of the side lobes or spectral leakage. This phenomenon gives rise to the interpretation of side lobes as spurious frequencies introduced into the signal by the abrupt truncation that occurs when a rectangular window is used. For nonrectangular windows, the end points of the truncated signal are attenuated smoothly, and hence the spurious frequencies introduced are much less severe. On the other hand, nonrectangular windows also broaden the main lobe, which results in a net reduction of resolution.

Let us consider a signal $v(t)$ as a sum of P complex sinusoids and white noise:

$$v(t)=\sum_{h=1}^{P} V_h e^{j(2\pi f_h t+\varphi_h)} \tag{1}$$

where V_h, f_h, φ_h are the amplitude, frequency, and the phase of the h^{th} voltage, respectively. The periodogram, defined as follows:

$$\hat{P}(f)=\frac{1}{N}|V_N(f)|^2 \tag{2}$$

where $V_N(f)=\sum\limits_{k=0}^{N-1} v_N(k)e^{-j2\pi kf}$, $k=0,1,\dots,N-1$.

The windowing of signals is presented as fellows:

$$v(k)\cdot w(k)=v_w(k)\,. \tag{3}$$

The modified periodogram estimate of the PSD is

$$\hat{P}_w(f)=\frac{1}{SN}|V_w(f)|^2 \tag{4}$$

where S is the window normalization constant which is independent of the choice of window.

$$S=\frac{1}{N}\sum_{k=0}^{N-1}|w(k)|^2\,. \tag{5}$$

B. Averaged periodogram

The averaged periodogram or called a Welch estimator of the PSD consists of dividing the time series data N into k segments of length M.

$$v_M^{(i)}(k)=v_M(iM+k)\,,\quad 0\le i\le k-1\,,\ 0\le k\le M-1\,. \tag{6}$$

The multiplication of k segments of signal, $v(k)$, by a nonrectangular window, $w_M(k)$:

$$v_M^{(i)}(k)\cdot w_M(k)=v_w^{(i)}(k)\,. \tag{7}$$

Computing of each segment and then averaging the PSD estimates is the Welch PSD estimate.

$$\hat{P}_w(f)=\frac{1}{Sk}\sum\frac{|V_w^{(i)}(f)|^2}{M}\,, \tag{8}$$

$$S=\frac{1}{M}\sum_{k=0}^{M-1}w_M^2(k)\,. \tag{9}$$

The averaging of modified periodograms tends to decrease the variance of the estimate relative to a single periodogram estimate of the entire data record. Although the overlap between segments tends to introduce redundant information, this effect is diminished by the use of a nonrectangular window, which reduces the effect of the end samples of segments (the samples that overlap).

3 DETECTION OF VOLTAGES INDUCED IN STATOR WINDINGS

After supply disconnection, the currents in the stator windings are switched off while the rotor currents go exponentially to zero, depending on rotor electrical parameters. Until the rotor current extinguishes it is possible to measure the voltages induced in the stator windings.

The rotor MMF F_r, expressed in the rotor reference frame, is given by:

$$F_r=\sum_{n=1}^{\infty}F_{rn}\cos(np\theta+\psi_n) \tag{10}$$

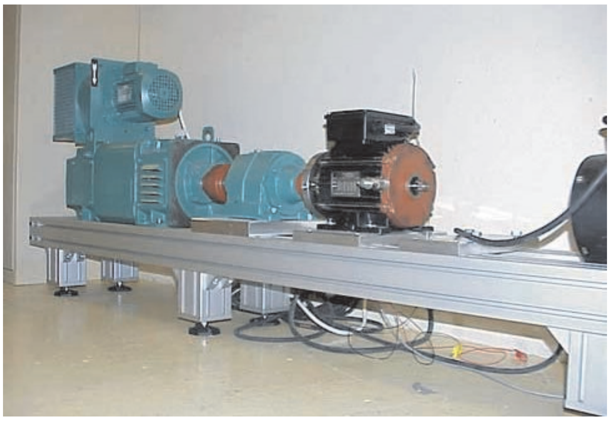

Fig. 1. Test bench for a generation of faults

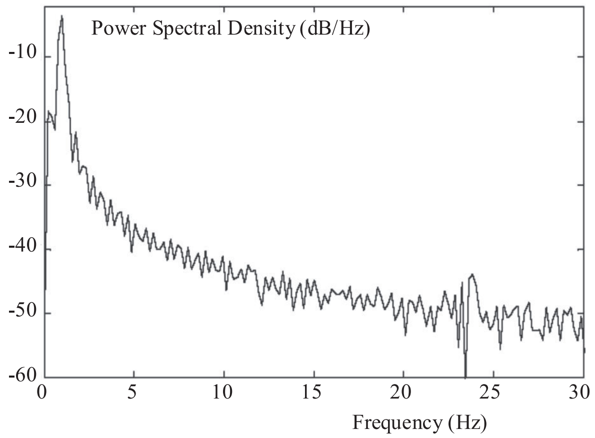

Fig. 2. Periodogram PSD estimate Rectangular window and healthy cage

where p is the number of pole pairs, n is the harmonic order number, and θ is the angular position with respect to the rotor. For a healthy motor, it is possible to demonstrate that the principal harmonics which contribute to the MMF, have the following order number n:

$$n = k\Big(\frac{R}{p}\Big) \pm 1 \tag{11}$$

where R is the number of the rotor bars and $k = 1, 2, 3 \dots$. The rotor MMF, in the stator reference frame, is

$$F_r^s = \sum_{n=1}^{\infty} F_{rn} \cos\big(np(\theta + \omega_r t) + \varphi_n\big) \,. \tag{12}$$

The MMF harmonics generate harmonic flux components.

Only some particular harmonic flux components are able to induce voltages in stator windings and are identified by the following order number $6m \pm 1$, with $m = 1, 2, 3 \dots$. The broken rotor bars produce noticeable amplitude harmonics in the rotor MMF and flux. These harmonics are not necessarily included in (12). Nevertheless, also in this case the harmonic flux components able to induce voltages in the stator windings have orders given by $6m \pm 1$. Also, in a healthy motor the rotor is not perfectly symmetric, but the flux harmonics have a small amplitude. Therefore, the presence of broken rotor bars is detectable by monitoring the amplitude of voltage harmonics induced in the stator windings with index equal to $6m \pm 1$. The rotor currents rapidly extinguish. If the window size is chosen too large, the signals cannot be considered stationary. In this paper, the modified periodogram and averaged $m \pm 1$ periodogram are used, instead of the direct use of the FFT, to improve the detection of the fault index $6m \pm 1$, particularly the 5^{th} and 7^{th} voltage harmonics.

4 EXPERIMENTAL RESULTS

The induction machines used to test the diagnostic is a 1.1 kW induction motor (Fig. 1). The motor is supplied by the voltage, with no load attached on the shaft. One-phase voltage is measured and stored in the computer memory.

Spectral analysis was performed on one-phase voltage. The frequency components given by $6m \pm 1$, with $m = 1, 2, 3 \dots$ are present both in the spectrum of the healthy and of the faulty motor. This is because stator and rotor circuits are not perfectly symmetric. When there are broken rotor bars, the amplitudes of these harmonics grow.

The amplitudes of these have been used in literature to identify the presence of broken rotor bars. In this case there is a need for preliminary investigation to detect which of the frequency harmonics increase more with the fault on the rotor . In this paper, it is proposed to show the harmonics of tension of odd order, in particular those of the low frequency, the 5^{th} and the 7^{th} harmonics.

The stator voltage is sampled with frequency 5 kHz. In this way the fifth and seventh harmonic components, if present among the principal sinusoidal components estimated by non parametric method, can be used to extract fault information.

One of the key points of this diagnostic technique requires a compromise stationnarity of the signal and its spectral resolution. If the time window size is chosen too large, the signal cannot be considered stationary because both its frequency and amplitude are decreasing with time; if it is chosen too small, the frequency resolution of the FFT is poor. The minimal distance which separates two consecutive frequencies $6m \pm 1$ is 100 Hz, this one must be higher than fs/N. In our case the sampling rate $f_s = 5$ kHz, the number of samples which allows distinguished principal frequencies is $N = 256$.

In order to identify the harmonic components due to fault, the minimum window time length that has given satisfactory results is $2^8/5000$ s, and is used in all the spectral analyses shown next. The overlapping is chosen at 50 % (*ie* , two segments).

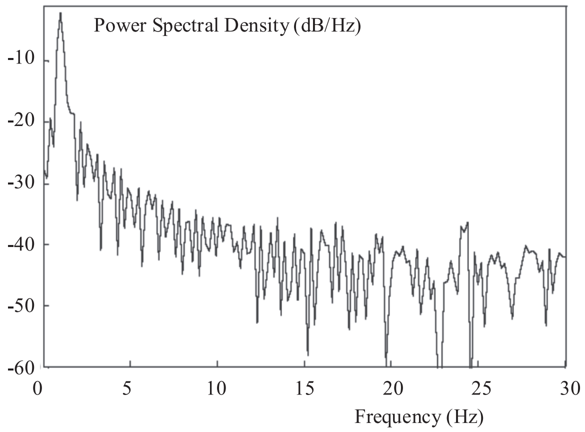

Fig. 3. Periodogram PSD estimate Rectangular window and three broken bars

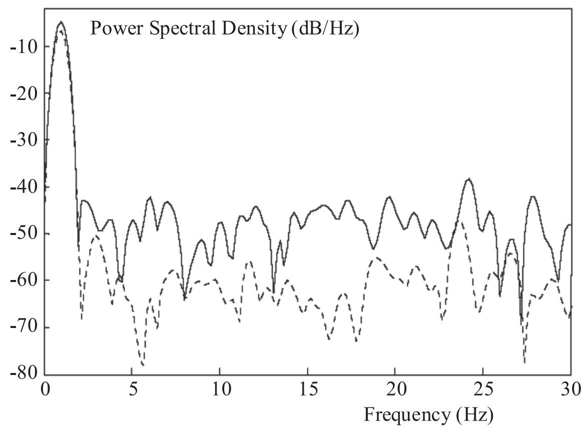

Fig. 4. Periodogram PSD estimate with Parzen window, healthy cge (dashed), with three broken bars (solid)

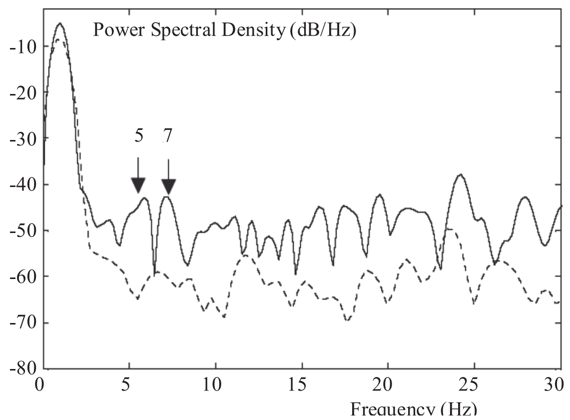

Fig. 5. Welch PSD estimate with Parzen window healthy cage (dashed), with three broken bars (solid)

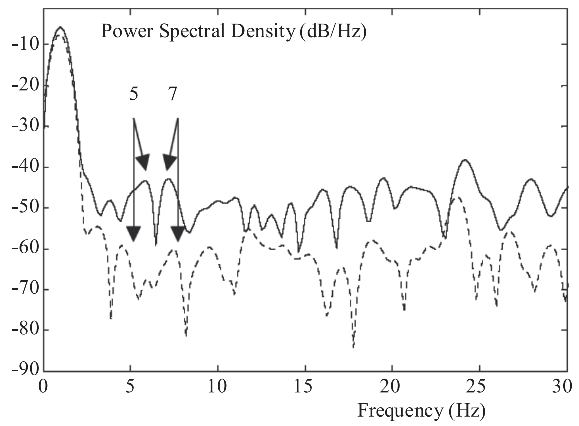

Fig. 6. Welch PSD estimate with Kaiser window healthy cage (dashed), with three broken bars (solid)

Due to the number of samples and to the sampling frequency, the frequency resolution of the FFT is equal to 20 Hz, and is too large to allow correct detection of the odd harmonic amplitudes. Figure 2 shows the periodogram PSD estimate with a rectangular window obtained on a healthy cage of the induction motor.

The same case is in the Fig. 3. but with three broken bars, it is noted that the voltage harmonics do not appear in the modified periodogram. This is due to the height of the side lobes or spectral leakage caused by the abrupt truncation of the signal with the rectangular window.

Figure 4. shows the periodogram PSD estimate with a nonrectangular window (Parzen). The end points of the truncated signal are attenuated smoothly, and the principal odd harmonics become clear but not sufficiently.

Figure 5 shows the Welch PSD estimate with Parzen window. The principal voltage harmonics are well shown, particularly the 5^{th} and the 7^{th} in the faulty case and not in healthy case.

In Fig. 6 the detection of the 5^{th} and 7^{th} in both broken bars and healthy cage is improved with the Welch PSD estimate and Kaiser window.

5 CONCLUSION

This paper has described a method for improving the detection of the 5^{th} and 7^{th} voltage harmonics induced in stator windings, after supply disconnection, to detect broken bars in a squirrel-cage induction motor. The modified periodogram PSD allows one to estimate harmonics due to a fault but those of low frequencies are not well shown. The Welsh algorithm with Parzen window estimates clearly the 5^{th} and 7^{th} harmonics but only in the broken bars case. In order to detect these harmonics in both faulty and healthy cases the Kaiser window is well adapted for this application.

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