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Research Article

A New Indicator for Rotor Asymmetries in Induction Machines Based on Line Neutral Voltage

[1]Khalid Dahi, [1]Soumia El Hani, [2]Said Guedira and [1]Ilias Ouachtouk
[1]Electrical Engineering Research Laboratory, Mohammed V University in Rabat, 10110, Morocco
[2]National School of Mineral Industry, Rabat, 10110, Morocco

Abstract: Induction Machines (IMs) are the most used electric machines in various industrial applications. An improved approach is proposed in this study for rotor asymmetry detection in IM using the line neutral voltage; this method is based on the analysis of the potential difference between the null point of the supply voltage system and the neutral of the star connection of IM stator winding; fault detection in this study is based on monitoring of the standard deviation calculations taken on two frequency ranges where are located the most sensitive harmonics to the occurrence of rotor asymmetry. The proposed method can be a helpful tool to the decision making without need any reference, which represent its main advantage compared to other fault indicators. The effectiveness of the developed indicator is demonstrated on IM test bench with rotor asymmetry.

Keywords: Diagnosis, induction machine, line neutral voltage, rotor asymmetry

INTRODUCTION

Induction Machine are widely used in industry as the most used Electrical Machines (EM). They represent about ~90% of the consumed power in industries thanks to their low cost, reasonable size and low maintenance. However, they suffer from some electric stresses that can affect the profitability of these machines (Capolino *et al*., 2015; Zhang *et al*., 2011).

Condition monitoring of electric machines can significantly improve the reliability and enable unexpected shutdown, particularly in case of high-power EM.

Studies carried out by relevant articles in the area of diagnosis and monitoring of rotating machines have shown that stator windings and rotor windings faults are assumed equal because they are inadequately protected. However, the vast majority of articles dealing mainly with rotor fault (69%) first and then with stator faults and finally bearing faults (Nandi *et al*., 2005).

Being the topic so important, this study investigates the rotor fault detection in IM, this fault that physically result either by short/open circuits or by increasing of the rotor resistance.

Motor Current Signature Analysis (MCSA) is the most commonly used technique and well known one. In fact, Schoen *et al*. (1995) have addressed the implementation of the MCSA for bearing fault detection in IM. This study examines the effectiveness of the current monitoring to support fault detection. MCSA is simple and effective in appropriate operating conditions (Didier *et al*., 2007). However, from an industrial point of view, this technique faces significant practical limitations due to the increasing complexity of EM and drives:

- MCSA is influenced by the operating conditions. For example, in case of rotor asymmetries faults in motors working at a very low load, the main frequency component may hide the fault harmonics because their frequency is close to the main frequency of the power supply.
- The diagnosis is really difficult if the IM is supplied by a power converter or if the IM operates in a system under time-varying conditions.
- Recently, The IM are frequently installed with inverters which provide some advantages but makes the stator current inaccessible to diagnosis.

To overcome these limitations, the proposed work focuses on the use of line neutral voltage as a measurable quantity (Razik and Didier, 2004; Jung *et al*., 2006; Oumaamar *et al*., 2006, 2007, 2011). The method has performance comparable to MCSA or better, this method is based on the analysis of the potential difference between the null point of the supply

Corresponding Author: Khalid Dahi, Electrical Engineering Research Laboratory, Mohammed V University in Rabat, 10110, Morocco

voltage system and the neutral of the star connection of IM stator winding, or artificial neutral in the case of a supply voltage by inverter in order to detect a rotor fault in IM.

Classical techniques gives information about the presence of fault but no direct fault detection criterion is provided. Consequently, additional post-processing algorithms are required to determine the fault-related frequencies (mainly done manually) and to extract a fault detection criterion.

For that, by using the FFT Phase we develop a method by Neutral Voltage Signature Analysis (NVSA) for the detection of rotor asymmetries without need any reference, this reference obtained in a healthy functioning of the motor. This approach is based on standard deviation calculations taken on two frequency ranges, the first standard deviation will be calculated on the first frequency range, this range identifies where the phase jump whose frequency $(3-4s)fs$. The second standard deviation is a picture of measurement noise present between jumps being located at frequencies $(3-4s)fs$ and $(3-6s)fs$. Thereafter, an analysis of phase spectra by the Hilbert transform is made, this transform is usually used in image processing, where the phase contains more relevant information than its module, the HT is calculated from the amplitude spectrum of the signal to analyze, which allows to conclude on the nature of fault and gives better results than FFT based phase.

Our major contributions in this study are threefold: We propose a method based on spectral analysis for the decision making about the state of machine without need any reference, we apply this approach on rotor faults in IM using the NVSA and we prove the effectiveness of the technique on experimental data.

MATERIALS AND METHODS

This section present some mathematical signal processing notions used to develop the proposed method.

Fourier transform: The equation of the Fourier Transform (FT) is given by:

$$F(k) = \frac{1}{N}\sum_{n=0}^{N-1} p_s(n) e^{-j\frac{2\pi nk}{N}} \tag{1}$$

The result given by this equation is a complex signal with a real part and an imaginary part:

$$F(k) = \Re(F(k)) + j\Im(F(k)) \tag{2}$$

Then, the phase of the FT is given by:

$$\varphi_{FT}(k) = \arctan\left(\frac{F_{\mathrm{Im}(k)}}{F_{\mathrm{Re}(k)}}\right) \tag{3}$$

Hilbert transform: Let's consider a real measurement signal: $x(t) \in L^{(2)}$.
where, $L^{(2)}$ is the signal class with integral square.
The Hilbert transform of the signal $x(t)$ is given by:

$$\tilde{x}(t) = H\{x(t)\} = \int_{-\infty}^{\infty} \frac{x(\tau)}{\pi(t-\tau)} d\tau \tag{4}$$

The analytic signal $z(t)$ is built using the Hilbert Transform of $x(t)$, $z(t)$ *is* associated with $x(t)$ and defined as:

$$z(t) = x(t) + j\tilde{x}(t) \tag{5}$$

That can be rewritten also as:

$$z(t) = A(t) * e^{j\theta(t)} \tag{6}$$

$A(t)$ is called the envelope signal of $x(t)$ and $\theta(t)$ is called the instantaneous phase signal of $x(t)$.

The use of Hilbert phase analysis is applied to the module of Fourier transformation frequency of the signal $x(t)$. Indeed, the analytic signal and the corresponding phase are given by:

$$A(t) = [x^2(t) + \tilde{x}(t)]^{1/2} \tag{7}$$

$$\varphi(t) = \tan^{-1}\left[\frac{\tilde{x}(t)}{x(t)}\right] \tag{8}$$

Or:

$$\varphi(f) = \arctan\frac{H\left[|X(f)|\right]}{|X(f)|} \tag{9}$$

Harmonics showing rotor asymmetry in line neutral voltage: MCSA is the most dominant diagnosis method used in the area of IM monitoring, as stated by Capolino *et al*. (2015). MCSA is based in the monitoring of harmonics which contain the characteristic frequencies of the concerned fault. In case of rotor faults (Broken rotor bar, broken end ring, resistance connections …), they can be detected from the presence of fault harmonics in line current spectrum given by:

$$f_{asym} = f_s \pm 2ksf_s \tag{10}$$

s : Slip
f_s : Supply frequency, k = 1, 3, 5, ...

These harmonics are located in the stator current spectrum around all Rotor Slot Harmonic (RSH). For a Healthy machine it has been shown that the RSH are generated in the stator current (Razik and Didier, 2004):

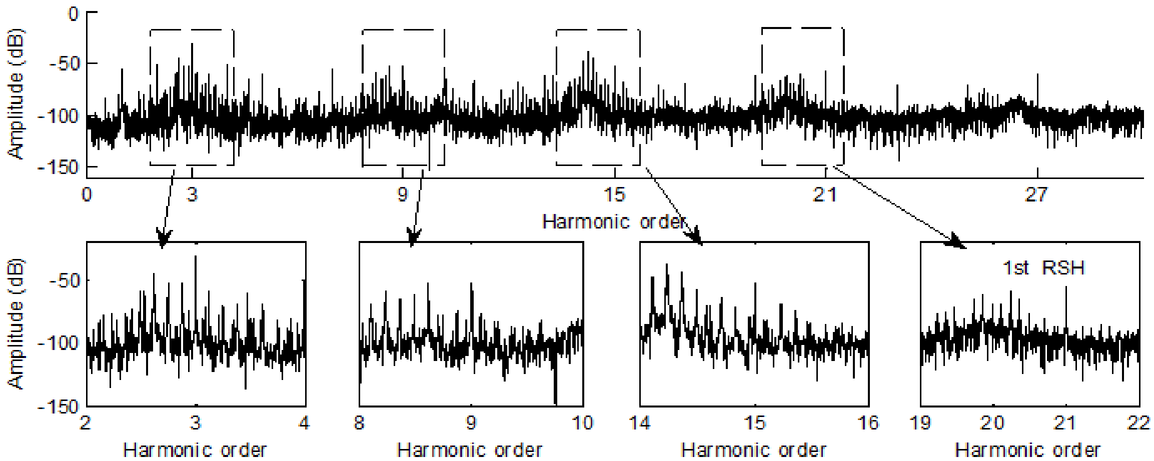


Fig. 1: Spectrum of the line neutral voltage under rotor asymmetry

$$f_{sh} = f_s\left[\lambda \frac{N_r}{p}(1-s) \pm 1\right] \tag{11}$$

Concerning the machine acting with rotor asymmetry (broken bar, end-ring fault or eccentricity), Thomson *et al*. (1999) have shown that the rotor slot harmonic frequencies are:

$$f_{sh} = f_s\left[\lambda \frac{N_r}{p}(1-s) \pm 1 \pm 2ks\right] \tag{12}$$

λ is a positive integer, N_r is the number of rotor bars, p is the number of pole pairs and s the slip.

The analysis of line Neutral Voltage signatures still remains far from being finished and efforts are in progress to improve the overall fault diagnosis of induction machines. In this study, the authors propose an analytical investigation of the generation mechanism of different harmonics due to rotor faults.

The first research conducted for the diagnosis using line neutral voltage dates at 1998 with the works of Cash *et al*. (1998), this study used the voltage between the neutral of the supply voltage and the neutral of induction machines to detect short circuits between spirals in stator coils. Years later, in 2007, A similar analysis was carried out by Oumaamar *et al*. (2007) in order to detect rotor fault in induction motors.

In simulation, the voltage between the neutral supply and the neutral of the induction motor of the power source is given by the following mathematical relationship:

$$V_{NN} = R_a I_{sa} + L_a.\frac{dI_{sa}}{dt} + \frac{dL_a}{d\theta}\Omega I_{sa} - V_{Supply} \tag{13}$$

where:

R_a : Represents the stator-phase resistance
L_a : His inductance
I_{sa} : The current passing through it
Ω : Rotation speed, θ the angular position of the rotor and V_{supply} simple voltage generated by network supply.

The presence of a fault rotor reveals additional components in the spectrum of neutral voltage. Indeed, Oumaamar *et al*. (2007) demonstrated by a complex analysis, that the appearance of a rotor fault induces additional components in the frequency spectrum of the NV at frequencies given by the relation:

$$f_{asym,NV} = \left[3h - (3h \pm 1)s\right] f_s \tag{14}$$

s : Slip
f_s : Supply frequency, h = 1, 3, 5, ...

This study uses the information given by the spectrum of the NV around the third harmonic, i.e., nears the spectral line having the frequency 150 Hz. Figure 1 show the power spectral density of the line neutral voltage in case of machine acting with rotor asymmetry (3 broken rotor bars).

Table 1 show the presence of the main frequency component (14) and additional components around these main components.

It is important to note that is in case of wound rotor induction machine (WRIM), the rotor asymmetry is created by adding an extra resistance on one of the rotor phase (Ngote *et al*., 2014; Dahi *et al*., 2014a).

Proposed method: A review in the literature show that the detection of rotor fault is possible by evaluating the magnitude of sidebands frequency $f1 = (1 - 2s)fs$ as fault indicators in case of MCSA. However, Benbouzid (2000) have reported that the frequency f_1 can be insufficient for correct detection of

Table 1: Example of frequency components of line neutral voltage around the third harmonic in case of rotor asymmetry

	Fault component		
Order	Related frequency	Frequency (Hz)	Amplitude (dB)
1st Order (k = 1)	$(3\text{-}2s)f_s$	145.23	-54.38
2nd Order (k = 2)	$(3\text{-}4s)f_s$	139.19	-50.21
3rd Order (k = 3)	$(3\text{-}6s)f_s$	133.41	-48.69

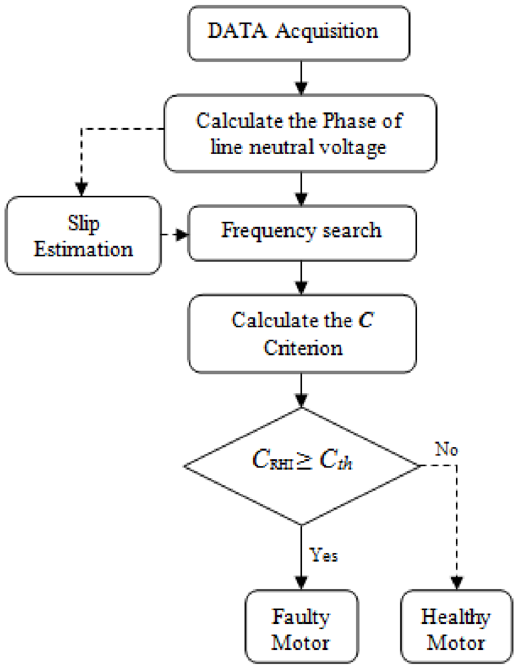


Fig. 2: Flowchart of the proposed method

rotor faults and additional sidebands especially around the 5th and 7th harmonic, may be significantly useful for rotor faults diagnosis.

On this context, this study investigates an improved and robust algorithm for the detection of rotor faults in induction motors. For that, this study proposes an algorithm to decision making by analyzing the exclusive line between neutrals signal. The proposed fault detection algorithm is described in Fig. 2.

We study first the phase φ_F (f), particularly the jump present at the frequency $(3-4s)fs$; according to (14); which can inform about the motor state because it is react considerably to the presence of rotor fault even in case of machine acting under low load.

Estimation of motor slip: As previously announced, the proposed method is based on the analysis of the jump $(3-4s)fs$ which is function of the motor slip s. There are several methods to calculate the slip of the IM, the easiest way is the use of a speed sensor in case of experiment test. This study uses some harmonics to estimate the slip. The line neutral voltage of IM contains a great number of RSH.

The principal RSH found on the spectrum can be derived as:

$$f_{sh} = f_s\left[\lambda\frac{N_r}{p}(1-s)\pm 1\pm 2ks\right] \tag{15}$$

And the slip can be expressed as:

$$s = 1-\frac{p}{N_r}\left[\frac{f_{RSH}}{f_s}\pm 1\right] \tag{16}$$

Generally, all induction machines have a slight asymmetry of construction that induced, in the spectrum of NV, the appearance of the frequency component $(3-2s)fs$, therefore, the slip $s$can be calculated from the formula given by:

$$s = \frac{1}{2}\left[3-\frac{f_{RSH}}{f_s}\right] \tag{17}$$

However, the frequency of this component changes according to the variation of the motor load. In this case, a searching interval is defined; their boundaries depend on the max and min values of the slip s_{min} and s_{max}; these correspond to unloaded machine and full load machine respectively.

Consequently, the searching frequency belongs to the following interval:

$$f_{search} \in \left[(3-2s_{\max})fs...(3-2s_{\min})fs\right] \tag{18}$$

In our case, given that we know the fundamental frequency f_s and as our machine is operating with a nominal speed of 2800 rpm which gives a minimum frequency f_{search} equal to 143,6Hz, therefore, the range selected for the detection of this jump will be [140,150] Hz.

Standard deviation calculation: The next step is to identify the value of the $(3-2s)fs$ component and its amplitude in the spectrum of the line neutral voltage, the perfect way to do this is to define a frequency range corresponding to the wanted harmonic, this component which has the highest magnitude nearest the 3rd harmonic in the interval defined as:

$$R = \left[f_{tar}-i\Delta f \quad ; \quad f_{tar}+j\Delta f\right] \tag{19}$$

where,

f_{tar} : Target harmonic obtained via the estimated slip

Δf : The frequency resolution ($\Delta f = fs/N$), i and j are integers.

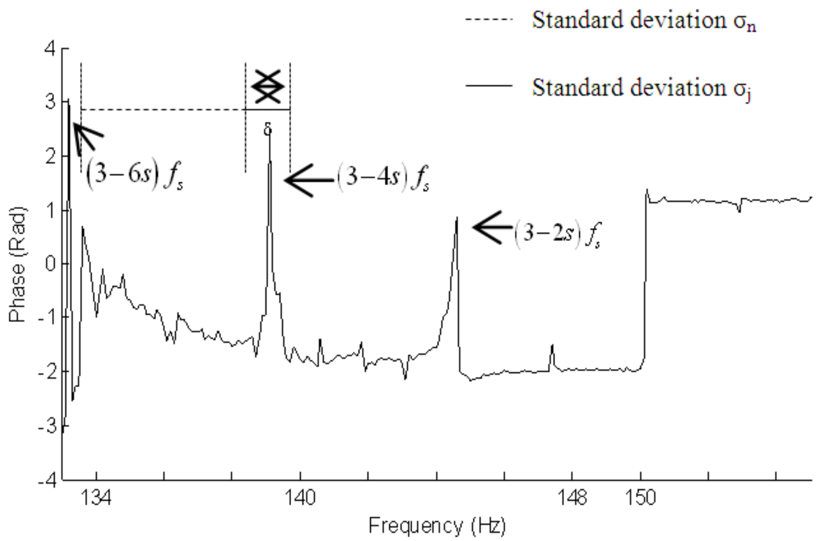


Fig. 3: Calculation of standard deviations σ_j and σ_n

Once the slip is determined, We compare the standard deviation of the phase $\varphi_H(f)$ and the phase $\varphi_F(f)$ based on two different frequency ranges. Indeed, the first standard deviation, noted σ_j will be calculated on the frequency range ($BW1$), this range identifies where is the phase jump whose frequency $(3-4s)fs$. The second standard deviation, which we note σ_n will be calculated on the frequency range ($BW2$), this standard deviation is a picture of measurement noise present between jumps being located at frequencies $(3-4s)fs$ and the next jump $(3-6s)fs$:

$$BW1 = \left[(3-4s)f_s - \frac{\delta}{2} \quad , \quad (3-4s)f_s + \frac{\delta}{2} \right]$$
$$BW1 = \left[(3-4s)f_s + \frac{\delta}{2} \quad , \quad (3-6s)f_s + \frac{\delta}{2} \right] \tag{20}$$

The mathematical relationship to calculate the standard deviation σ_v, unbiased, of the Neutral Voltage is:

$$\sigma_v = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(v_n - \frac{1}{N}\sum_{i=1}^{N} v_n\right)^2} \tag{21}$$

Figure 3 shows a representation for an adequate understanding of the calculation of these deviations. The standard deviation σ_j is calculated on the gray frequency range while the standard deviation σ_n is calculated on the black frequency range.

Fault decision: In order to make our indicator more robust and to limit false alarms detection, a threshold has been introduced in the criterion that will symbolize with: C_{th}. This threshold compares the variance σ_j with the variance $\sigma_n$of $\varphi_F(f)$. Therefore, the authors have defined the following criterion (Table 2):

Table 2: Rotor asymmetry decision

Criterion	Rotor state
$C_{RF} \leq C_{th}$	Healthy rotor
$C_{RF} \geq C_{th}$	Defective rotor

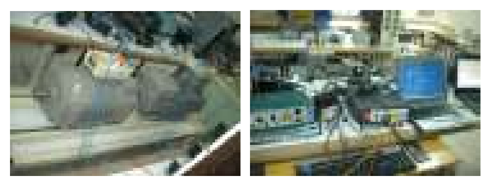


Fig. 4: Experimental setup

Where $C_{RF} = \sigma_j/\sigma_n$ and C_{th} is the sensitivity degree of our fault detection indicator and it is determined in function of the studied IM. Both, the rotor fault index C_{RF} and the corresponding threshold parameter C_{th} are determined from experimental results based on the signal detection theory.

Experimental Setup: Figure 4 shows the experimental setup used in this test. This setup was developed in the CPS2I laboratory (Higher National School of Mines in Rabat, Morocco).

Experimental Tests were developed on a 3kW, 50Hz, 220V = 380V, 4-poles Induction Machine. The motor was driving a DC machine acting as a load. Two voltage sensors are used to monitor the induction machine operation. The IM voltages are measured by means of the two sensors which are used as inputs of the signal conditioning and the data acquisition board integrated into a personal computer. For those two variables, the sampling frequency was *26* kHz and each data length was equal to 2^{14} values. Eight data sets of induction machines neutral voltage subject to different numbers of rotor fault and load conditions were analyzed (Table 3).

Table 3: Analyzed data sets

Set	Machine condition
s1	Healthy, unloaded
s2	Healthy, 75% load
s3	Healthy, full load
s4	Fault, unloaded
s5	Fault, 75 % load, one broken rotor bar
s6	Fault, 75 % load, two broken rotor bar
s7	Fault, 75 % load, three broken rotor bar
s8	Fault, 100 % load, one broken rotor bar

RESULTS AND DISCUSSION

Fourier phase based method: First, we apply the Fourier phase to the neutral voltage signal of IM supplied directly by the network.

The results for this method are presented in Table 4, the rotor state is presented in the first column of this table, the second gives the value of the frequency $(3-2s)fs$, the third and fourth columns gives the values σ_j and σ_n calculated from $BW1$ and $BW2$, the fifth column gives the $\sigma j/\sigma n$ report that allows the decision making. Figure 5 shows the curve $\varphi_F(f)$ phases for different cases of rotor (s2, s4, s5, s6, s7 and s8).

In case of machine operating with a healthy rotor it is shown that the criterion C_{RF} is low according to the column giving this parameter. Note that for some rotor states we do not detect the jump phase $(3-2s)fs$, then we consider the rotor is healthy.

The appearance of a partial rotor fault does not induce a significant increase of σ_j relative to σ_n, which does not allow to conclude on such a failure, it may be the low point method using $\varphi_F(f)$. For an important rotor fault (s8) we note that this report is greater 10 times those in tests where the machine is healthy.

From these results, we can validate the proposed approach, even if C_{RF} in tests s6 and s5 is less pronounced as seen in Table 4, but the results are satisfactory.

The first problem for this approach is the high level of noise in the frequency range studied. The second problem is the wrong detection of the phase jump at frequencies located at frequency characterizing the rotor fault for the NVSA. In fact, the presence of random phase jumps in the frequency range does not allow proper detection of the phase jump required to calculate the slip.

Hilbert phase based method: It has been shown in the previous section that even the good results that phase spectrum analysis gives compared to the module spectrum analysis, this method has two drawbacks (Dahi *et al*., 2014b):

- The noise level is high, which makes detection difficult.
- The second is that the form of the phase is not fixed. Indeed, the real and imaginary parts can take random values.

To stabilize the form of phase, we must find a solution to control the values of the real and imaginary parts of the spectrum, the idea is to obtain a phase always equal to[$-\pi/2$] to the left of f_s and equal to [$\pi/2$] right f_s, the real part must be zero at frequencies $\pm f_{asym}$ and f_s.

These problems can be circumvented with the use of the Hilbert transform, as we will see below.

In order to support the results obtained, we give in Fig. 6 the curves of phase $\varphi_H(f)$ with different fault level. In these figures, we stand once again by a continuous gray line the frequency range where the standard deviation σ_j is calculated, for a continuous black line the frequency range where the standard deviation σ_n is calculated and a red line the maximum of the phase jump at the frequency located at $(3\text{-}2s)fs$.

By use of the Hilbert transform (Table 5), the two sets s4 and s5 were detected which is not the case using the Fourier transform. Except this particular case,

Table 4: Results of diagnostic method applied to the phase of the Fourier transform

Rotor state	$(3\text{-}2s)fs$. (Hz)	$(3\text{-}4s)fs$. (Hz)	σ_n	σ_j	σ_J/σ_N
s1	No max detection				
s2	No max detection				
s3	145.23	139.19	0.240	0.091	2.64
s5	144.40	138.81	0.065	0.063	1.03
s8	146.33	140.00	0.969	0.026	37.3
s4	144.40	138.81	0.240	0.091	2.64
s6	143.80	138.0	0.51	0.079	6.52
s7	142.95	137.31	0.42	0.051	8.34

Table 5: Results of diagnostic method applied to the phase of the Fourier transform

Rotor state	$(3\text{-}2s)fs$ (Hz)	$(3\text{-}4s)fs$ (Hz)	σ_n	σ_J	σ_J/σ_N
s1	No max detection				
s2	145.23	139.19	0.384	0.108	3.56
s3	145.23	139.19	0.105	0.073	1.45
s5	144.40	138.81	0.056	0.005	10.64
s8	146.33	140	0.29	0.003	79.30
s4	144.40	138.81	0.015	0.007	2.15
s6	143.8	138	0.302	0.006	48.01
s7	142.95	137.31	0.36	0.006	56.3

the results are better than those given in Table 4. This better detection is possible because the noise in the phase of the signal analysis is much less important when the machine is running at low load torque. In addition, it is important to note that the signals obtained by the Hilbert transform are much less noisy than those calculated from the Fourier transform.

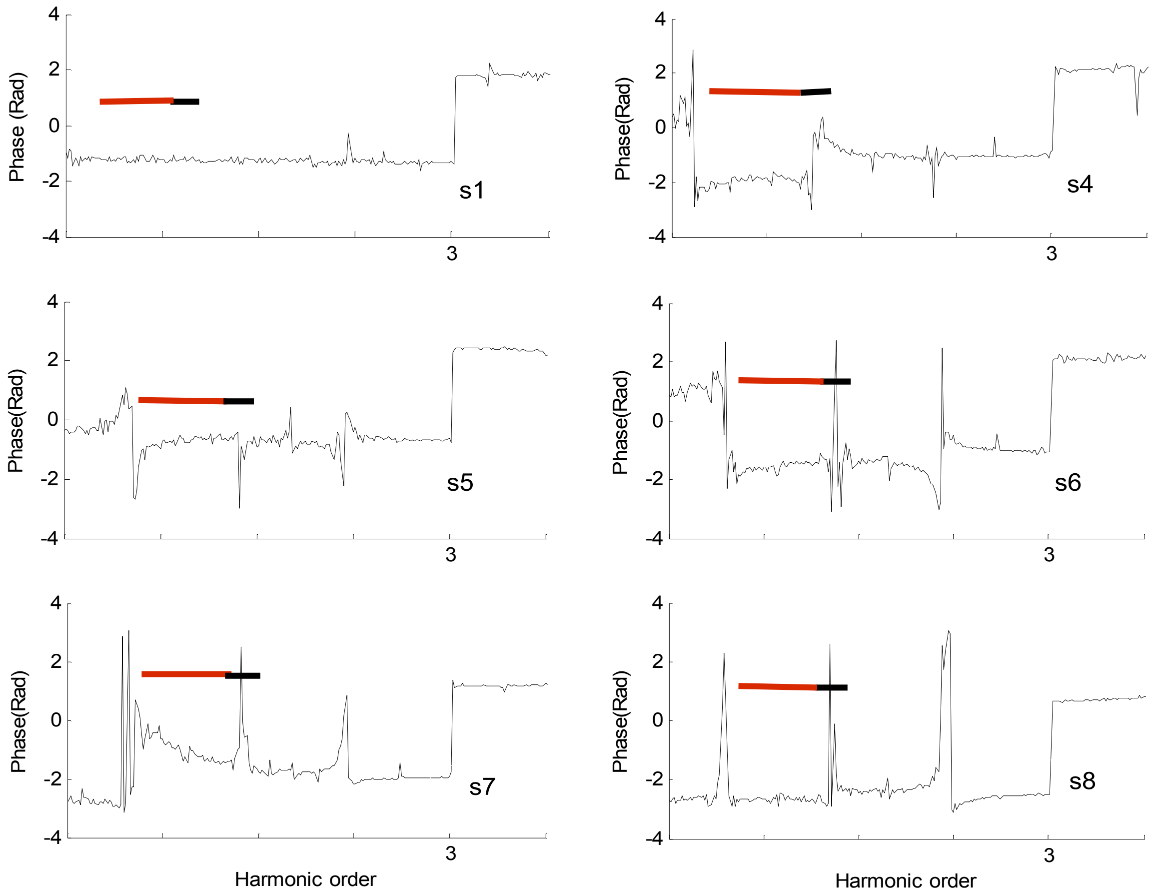
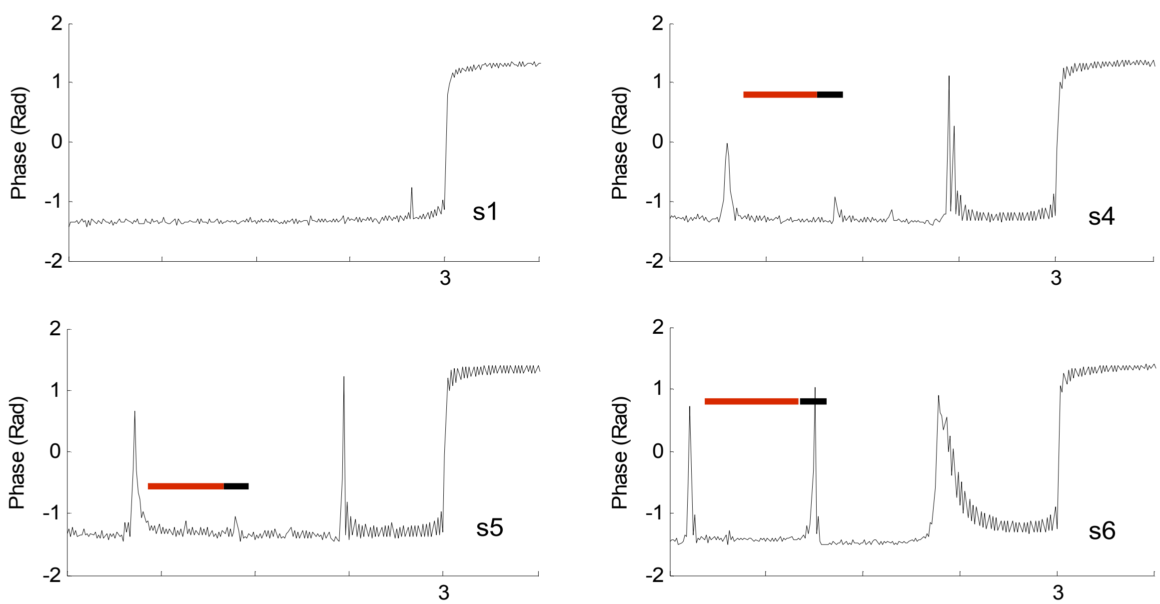


Fig. 5: Standard deviations σ_j and σ_n calculation by $\varphi_F(f)$



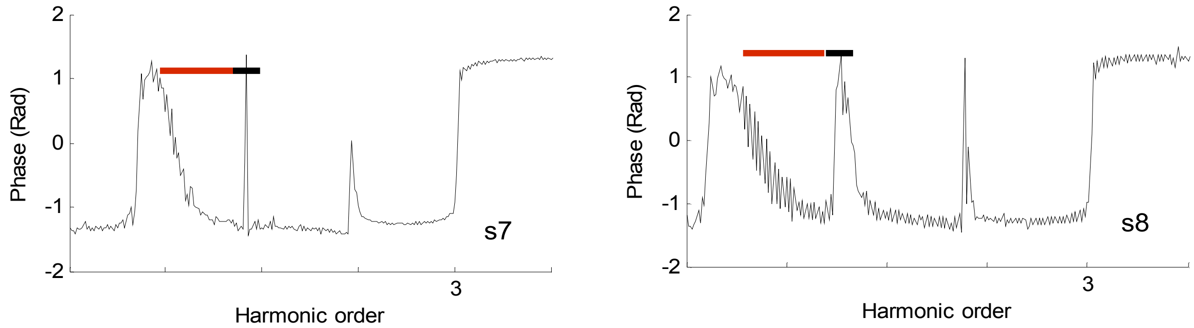


Fig. 6: Standard deviations σ_j and σ_n calculation by $\varphi_H(f)$

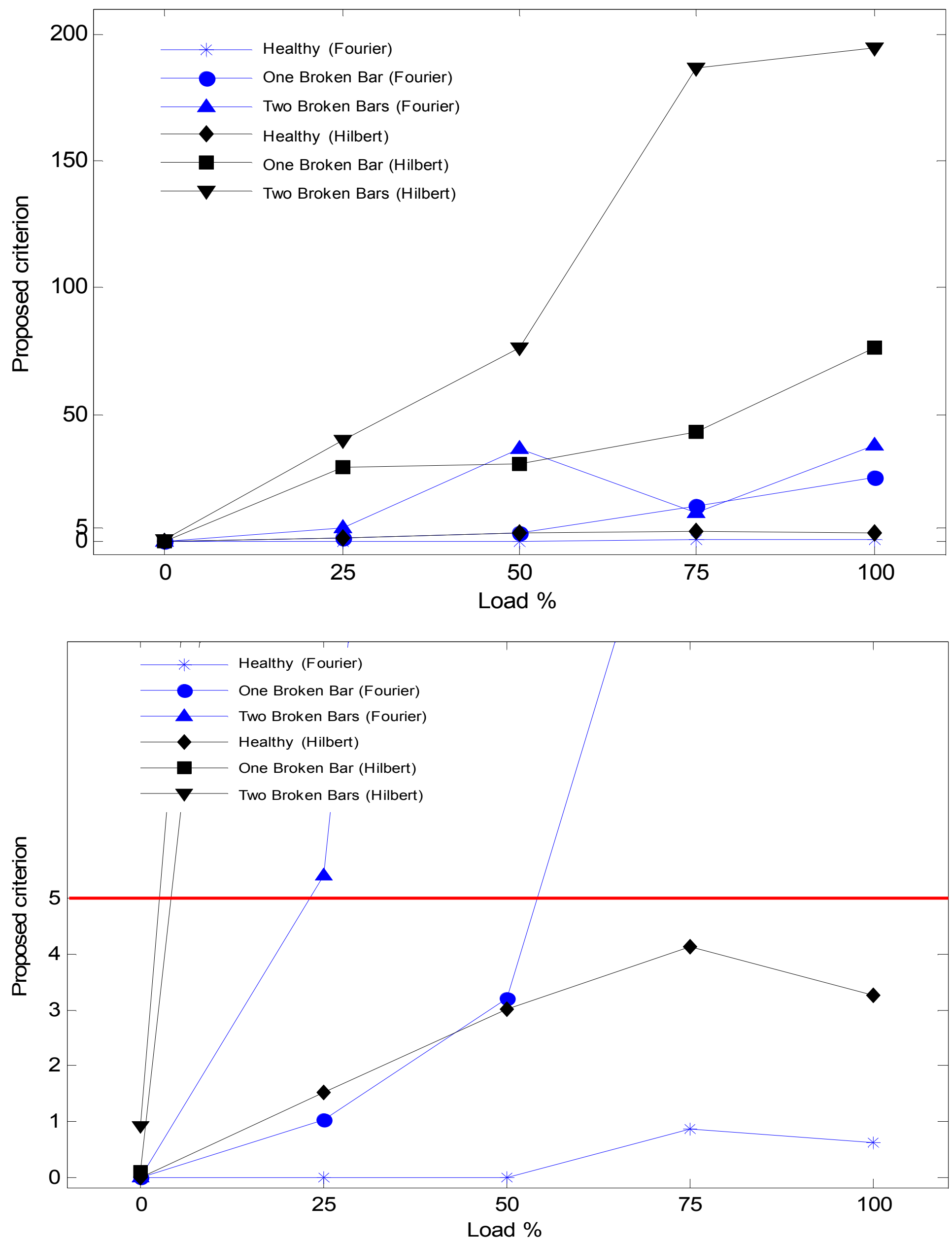


Fig. 7: Experimental variation of the proposed criterion according to the load percentage under different conditions (Left) and zoom (Right)

Table 6: The used value for C_{th}

Criterion	Rotor state
$C_{RF} \leq 5$	Healthy rotor
$C_{RF} \geq 5$	Defective rotor

We show in Fig. 7 a comparison between the Hilbert approach and Fourier one in both healthy and faulty cases. We note that the σ_j/σ_n report does not vary too much despite the variation in the load level. In the defective case we see a notable variation between fault conditions. From this figure, we note that the σ_j/σ_n report does not exceed 5 for a healthy machine and it is greater than *5* for a defective machine. This conclusion led us to make an induction machine diagnosis method without reference (this reference usually obtained from a healthy functioning). In other words if the report σ_j/σ_n is less than 5 then the machine is healthy and defective if greater than 5.

From this result we can draw a law diagnostic decision support according to Table 6.

CONCLUSION

In this study, a novel method for the rotor asymmetries diagnosis of induction motors has been proposed; it is based on the analysis of a new fault indicator that uses the line neutral voltage. It was shown in the study that the proposed indicator allows to have knowledge about the motor state, the fault severity and the corresponding slip for the data acquisition. This method is simple to implement and need just one sensor to acquire the line neutral voltage, compared to other fault detection methods, based on neural network or pattern recognition which have a difficult implementation using embedded devices with small internal memory such digital signal processors.

It would be interesting to validate this approach on asynchronous machines with different characteristics (higher power machines for example) to help determine a law of behavior for C_{th} parameter used in the detection criterion.

As perspective, it is envisaged to see how the inverter-fed condition affects the fault detection in induction motors to the proposed method.

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