An Improved Algorithm for Detection of Rotor Faults in Squirrel Cage Induction Motors Based on a New Fault Indicator

M. Sahraoui, S.E. Zouzou, A. Ghoggal, S. Guedidi and H. Derghal

Abstract – **In this paper an improved fault detection algorithm is proposed to ameliorate the reliability of the rotor fault detection task. The proposed algorithm uses the Motor Current Signature Analysis (MCSA); it is based on monitoring the Relative Harmonic Indexes (RHI) as a new fault indicator. The most sensitive harmonics to the occurrence of rotor bar faults contribute to the calculation process of the RHI, which represents its main advantage compared to the classical fault indicators. The proposed algorithm requires only the stator current signal as input. For each data acquisition, it estimates the slip, identifies the frequencies and the amplitudes of the searched harmonics then it computes the RHI. After that, the algorithm normalises and classifies the RHI. The obtained results are displayed on the monitor screen of the personal computer. For any data acquisition, the proposed algorithm allows the user to know the motor state, the fault severity and the slip. A lot of experimental tests, carried out on a 3kW squirrel cage induction motor, confirm the effectiveness of the proposed algorithm to detect rotor bar fault under different operation conditions even at very low loads.**

Index Terms--**Diagnosis, Induction motors, Broken rotor bars, Algorithm, Fault indicator.**

I. Introduction

One of the key elements in all industrial equipments is the induction motors. Usually, these machines work under many stresses from various natures (thermal, electrical, mechanical and environmental) which can involve the occurrence of stator and/or rotor faults that can lead to unexpected shutdown of the manufacturing process causing then considerable economic losses [6]. To avoid such problems, reliable diagnosis systems must be installed.

Generally, a diagnosis system must includes a robust fault detection algorithm, which allows detection of any defect, even with low severity, or any undesirable changes on the machine performances before a total failure. With such algorithm, it will be possible to program a shutdown of the manufacturing process in order to replace (if it is necessary) the faulty machine. This latter will be sent to repair shops, where it will undergo a precise inspection to locate and to repair the defects. Therefore, the great importance must be given to the fault detection task.

M. Sahraoui and A. Ghoggal are with Mentouri University, Constantine 25000, Algeria (e-mail: m_sahraoui@ieee.org, ghoetudes@yahoo.fr).

S.E. Zouzou and S. Guedidi are with Laboratoire de Génie Electrique de Biskra (LGEB), University of Biskra 07000, Algeria (e-mail: zouzou_s@Hotmail.com, guedidi.salim@hotmail.fr).

In the last twenty years, a lot of scientific papers have proposed and presented several detection methods [5],[6],[10]. It was observed that most of these methods belong to the signal approach. Their philosophy supposes that each fault is characterized by specific spectral signatures on the spectra of some motor signals (line current, vibration, torque…).

The rotor faults, like broken rotor bars, represent 5-10% of all induction motors failures [4],[6]. Using MCSA, the detection of such fault is possible by evaluating the magnitude of sidebands $(1 \pm 2s)f_s$ as fault indicators[3],[4],[7]. However, other researchers [2] have reported that $(1 \pm 2s)f_s$ can be insufficient for correct detection of rotor cage faults and additional sidebands, around the 5th and 7th time harmonic frequencies, may be significantly useful for rotor faults diagnosis[1],[8].

In this context, we propose the use of a new relevant fault indicator called Relative Harmonic Index (RHI), to detect cage rotor faults. The RHI is calculated using the amplitudes of some well selected harmonics. The choice of these harmonics is done according to their sensitivity to the occurrence of broken rotor bar; this choice is updated every data acquisition. This means that many particular current signatures contribute to the information given by this new fault indicator, which represents its main advantage compared to the classical fault indicators that are generally calculated using only one spectral component such as the $(1-2s)f_s$ or $(1+2s)f_s$.

However, a good diagnosis technique cannot lead, automatically, to a precise fault detection operation. In fact, the development of new diagnosis methods and the definition of pertinent fault indicators are only the first steps toward reliable fault detection results; the next step should be the elaboration of algorithms that exploit these techniques and indicators in order to give users the possibility to do a fast and reliable fault diagnosis[9].

On this context, the present paper proposes an improved and robust algorithm for the detection of rotor faults, such as broken rotor bars, in induction motors. The proposed algorithm requires only the stator current signal as input. It is based on the monitoring of the proposed fault indicator (RHI) every data acquisition. The algorithm classifies and normalises the obtained RHI, then it displays the results in an interactive manner that allows the user to know the motor state, the fault severity and the slip corresponding to any data acquisition. Consequently, the separation between the healthy and faulty conditions becomes fast and more easy.

An experimental work is performed on a three-phase 3kW squirrel cage induction motor. A lot of tests under different working conditions are carried out. The obtained results confirm the robustness and the effectiveness of the proposed algorithm.

II. Spectral Contents Of Stator Current

As well known, the MCSA is one of the most powerful methods of motor faults diagnosis [4]. This method uses the current spectra of one phase, which contains potential information of most motor faults. It doesn't need any estimation of motor parameters and it requires only a simple current sensor.

Because the proposed fault detection algorithm will be applied on the stator current to detect rotor faults, it is important then to explore the spectral contents of this signal under healthy motor then with different faults.

A. Healthy Motor

For a healthy three-phase squirrel cage induction motor assumed to have three-phase symmetrical stator windings and fed by a balanced power supply which is, in practice, not purely sinusoidal but contains Time Harmonics (TH). Taking into account these harmonics, the general term's expression of the stator current can be written as:

$$\begin{aligned} i_s(t) &= \hat{i}_{TH}^{\nu}\cos\left(2\pi\nu f_s t - \varphi_{TH}^{\nu}\right) \\ &+ \hat{i}_{RSH}^{\nu}\cos\left[2\pi\left(\nu f_s \mp kN_r f_r\right)t - \varphi_{RSH}^{\nu}\right] \end{aligned} \tag{1}$$

with $\nu = 1,3,5,...$ is the time harmonics order, $\hat{i}_{TH}^{\nu}$ denote the amplitude of the time harmonic components, $\hat{i}_{RSH}^{\nu}$ is the amplitude of the Rotor Slot Harmonic (RSH) associated to ν, N_r is the number of the rotor slots, φ is the phase angle and k is an integer.

Equation (1) shows that the stator current of a healthy motor contains infinite series of two harmonic types: TH and RSH. The TH are generated mainly from the power supply, while the RSH are the consequence of the discrete distribution of the rotor bars into the rotor slots.

B. Motor with Broken Rotor Bars

The occurrence of broken rotor bars introduces geometric and magnetic unbalances in the rotor side. Indeed, this fault causes asymmetrical rotor MMF, and this leads to an additional backward and forward rotor flux density waves which induce new current components, that we called Rotor Bar Fault Harmonics (RBFH), with particular frequencies given by:

$$f_{RBFH} = \left(\nu \pm 2ks\right)f_s \tag{2}$$

C. Motor with Eccentricity Faults

Machine eccentricity is the condition of the unequal air-gap that exists between the stator and rotor. There are two forms of air-gap eccentricity: static eccentricity and dynamic eccentricity. In practice, both of them exist together leading to the mixed eccentricity which gives rise to abnormal spectral components around the time harmonics. These components are called Eccentricity Fault Harmonics (EFH); their frequencies are given by:

$$f_{EFH} = \left(\nu f_s \pm k f_r\right) \tag{3}$$

III. Experimental Analysis Of The Stator Current

The test bench used in the experimental investigation is available in the LGEB at university of Biskra-Algeria (Fig.1). The motor exploited to study the occurrence of broken rotor bars is a three-phase 50-Hz, Y connection, 4-pole, 3kW *Leroy Somer* squirrel-cage induction machine. Several rotors of identical type could be interchanged. Each of them has 28 rotor bars. Separately excited DC generator feeding a variable resistor provides a mechanical load. The line current measurements are taken for different operating loads.

The motor was tested at healthy state, with one then two broken bars under different loads. In all cases, 10s of the three-phase currents are sampled at 10 kHz using a dSpace 1104 card. After acquisition, all data were processed using the MATLAB software package to compute the Fast Fourier Transform (FFT).

Fig. 1. The experimental test bench

A. Analysis of the Stator Current Spectrum

Initially, the motor was tested for a slip of about 3.8% under healthy state then with one broken bar. The obtained stator current spectra are visualized on Fig.2. As illustrated on this figure, one can clearly see the presence of the TH and RSH due to nonsinusoidal supply, discrete distribution of the rotor bars and saturation effect. In addition, RBFH and EFH appear also on the spectrum of the healthy motor, but with small magnitudes, due to the inherent asymmetries. Fig.2 shows also that the occurrence of a cracked bar causes significant increases on the magnitudes of the RBFH, which represent the theoretical signatures of this fault. However, it is important to know that not all RBFH are affected by the occurrence of broken bars, only some of them are considerably increased while the others are not. In order to illustrate quantitatively the spectral changes that are produced by this rotor fault, the stator current spectra of both healthy and faulty motor are compared, harmonic by harmonic, using the following Comparison Index (CI):

$$CI = \frac{A_{FS}}{A_{HS}} \tag{4}$$

With A_{HS} the amplitude of the target harmonic at healthy state (obtained from the reference spectrum) and A_{FS} the amplitude of the same harmonic at faulty state.

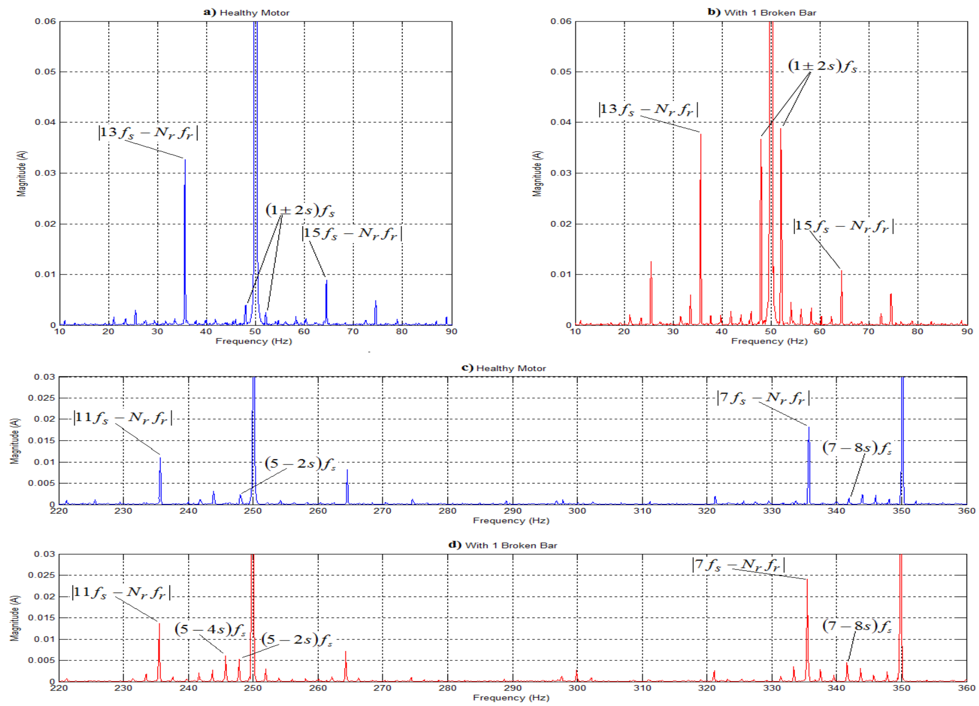

Fig.2. Stator current spectrum for healthy motor and with one broken bar

TABLE I. THE COMPARISON INDEX RELATED TO SOME SPECTRAL COMPONENTS FOR HIGH AND LOW LOAD

Harmonic Types	Some of the most sensitive components	Low load		High load	
		CI for one broken bar	*CI* for two broken bars	*CI* for one broken bar	*CI* for two broken bars
RBFH	$(1-2s)f_s$	3.65	4.74	14.60	18.44
	$(1+2s)f_s$	4.06	5.43	21.70	26.52
	$(1+4s)f_s$	5.51	6.91	9.50	11.70
	$(1-8s)f_s$	3.11	5.47	1.70	2.65
	$(5+2s)f_s$	3.58	5.11	7.06	8.78
	$(5-4s)f_s$	1.83	2.95	5.46	8.86
	$(5-8s)f_s$	2.78	4.40	1.38	2.50
	$(7-8s)f_s$	4.60	9.52	2.21	3.68

Using (4), we can define a CI for each spectral component; it is clear that each CI reflects the change that happens on the target harmonic due to the incidence of an abnormal condition. Some of the spectral components which are affected notably by the broken rotor bars are listed on Tab.I. According to this table, one can note that the CI's values depend strongly to the operating load and the fault severity. It is obvious that the information about the motor state are distributed on many spectral components. This imposes a problem about the component that should be used to detect rotor bar fault.

B. *The Use of the RHI for Rotor Fault Detection*

The classical way to detect a broken rotor bar in induction motors via the MCSA is based on using the amplitudes of the $(1-2s)f_s$ and/or $(1+2s)f_s$ to generate fault indicators. However, this method includes some practical problems. In fact and as shown previously, the occurrence of a rotor bar fault has affected a lot of spectral components and their sensitivities change according to the load, the fault severity and other factors related to the motor type and the conditions surrounding the application. For example, the $(1 \pm 2s)f_s$ sidebands can be considered as the best fault indicator for high loads but for low loads, other components like: $(7-8s)f_s$ and $(1+4s)f_s$ can inform us about the motor state because they react considerably to the presence of the rotor fault. In addition, the $(1 \pm 2s)f_s$ sidebands will be undetectable when the motor is operating at very low slip, which represent a serious problem for the classical fault indicators.

Therefore, it is not accepted to use only one or two harmonics to generate fault indicators since the information about the motor state is distributed on many other spectral components. Hence, an important question arises here: *how can collect the maximum of this information?*

The proposed solution is to use the Relative Harmonic Indexes (RHI). Since the incidence of broken rotor bars reveals significant increases on the RBFH, it is possible to define a Relative Harmonic Index (RHI_{RBFH}) computed starting from the CI of the most sensitive RBFH. This index can be calculated as follows:

$$RHI_{RBFH} = \frac{\sum^{m_{RBFH}} [CI \text{ } of \text{ } the \text{ } selected \text{ } components]}{m_{RBFH}} \qquad (5)$$

With m_{RBFH} specifies the number of the selected spectral components (the most sensitive).

It is important to note that the effectiveness of the proposed fault detection technique, depends strongly on the choice of the spectral components used to compute the RHI. We will return to this point in the next section.

In order to illustrate the efficiency of using the RHI, a lot of tests were carried out for different motor states (Healthy state **"HS"**, one broken bar **"1Bb"** and two broken bars **"2Bb"**) and different loads ($s = 0.039$, $s = 0.021$ then $s = 0.008$). After acquisition, the RHI_{RBFH} are calculated using (5) and they are visualised on Fig.3. This latter shows clearly that the RHI_{RBFH} increases substantially as a result of one broken bar even for small slip, and the magnitudes of this index increase as the rotor fault becomes more severe. Consequently, the separation between the healthy and faulty motor can be easily performed.

According to these important results, one can state that the RHI_{RBFH} provides meaningful information because it was computed starting from the most sensitive spectral components. Consequently, the monitoring of the RHI can be regarded as an excellent technique permitting a best exploitation of the stator current signal. This technique allows describing, in a qualitative and quantitative way, the motor state, making easier the separation of the faulty conditions from the normal conditions.

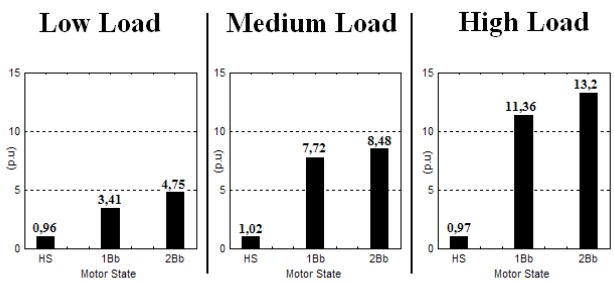

Fig.3. The obtained RHI corresponding to different motor state

V. THE PROPOSED FAULT DETECTION ALGORITHM

After describing the theoretical principle of the RHI and their use, it is important now to build an algorithm allowing the exploitation of this technique and this fault indicator to detect rotor faults in three-phase squirrel cage induction motors.

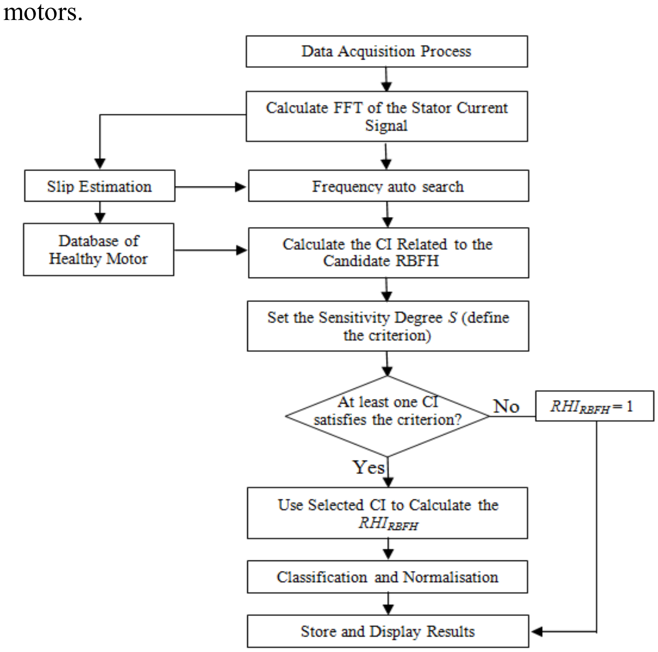

Fig.4. Flowchart of the proposed algorithm

Fig.4 shows the flowchart of the proposed fault detection algorithm; it is composed of four essential sections:
- Slip-estimation ;
- Frequency auto search;
- RHI calculation;
- Classification and normalisation;

For analyzing the harmonic contents of the line current signal in the frequency domain, we use the FFT which is a powerful and a simple signal processing tool. The important factors that must be considered are :

- The sampling frequency f_{samp}
- The frequency resolution Δf

For our case $f_{samp} = 10kHz$ and $\Delta f = 0.1Hz$.

A. Slip Estimation

As shown previously, the RBFH frequencies are function of slip. Hence, the diagnosis results using MCSA are wrong if the estimated slip is incorrect.

The slip is easily obtained from the output of the speed sensor (such as encoder), if the diagnosis process is included in a motor drive system. However, when the processing of the motor diagnosis is independent of motor drive system, slip information can be estimated from stator current spectra using some harmonic frequencies that are function of slip.

Usually, the line current of induction machines contains a great number of TH and RSH. The principal RSH found on the spectrum can be derived from (1) as:

$$f_{RSH} = \left[N_r \frac{(1-s)}{p} \pm 1 \right] f_s \qquad (6)$$

Consequently, the slip can be expressed as:

$$s = 1 - \frac{p}{N_r}\left(\frac{f_{RSH}}{f_s} \pm 1 \right) \qquad (7)$$

In addition, the electric machines have always some inherent rotor asymmetries permitting the appearance of RBFH and EFH on the stator current spectrum. Therefore, other slip formulas can be extracted from (2) and (3) as follows:

$$s = \pm \frac{1}{2}\left(\frac{f_{RBFH}}{f_s} - 1 \right) \qquad (8)$$

$$s = 1 \mp p\left(\frac{f_{EFH}}{f_s} - 1 \right) \qquad (9)$$

Remember here that we want to estimate the slip in order to identify the magnitudes and the frequencies of the RBFH, which are required to compute the RHI. For example, if we use (7) to obtain the slip information, we need to identify the f_{RSH} from the stator current spectrum. It is known that the frequency of this component changes according to the motor load. For that reason, a searching interval is defined; their boundaries depend on the max and min values of the slip. For our motor, the $s_{\min} = 0{,}0017$ and $s_{\max} = 0{,}046$; these correspond respectively to a very low load and the rated load. Consequently, the f_{RSH} belongs to the following interval:

$$f_{RSH} \in \left[\left(N_r \frac{(1-s_{\max})}{p} \pm 1 \right) f_s, \ldots\ldots, \left(N_r \frac{(1-s_{\min})}{p} \pm 1 \right) f_s \right] \qquad (10)$$

It is clear that the component which has the largest amplitude in this interval, certainly corresponds to the desired harmonic. The same technique can be applied to estimate the slip from the f_{RBFH} and f_{EFH}.

In order to confirm that the proposed slip estimator operates well, several tests are performed. Fig.5 shows a comparison between the estimated slip and the measured one, for six different loads. The obtained results show a very small average error (3.57%) which prove the precise of the proposed slip estimator.

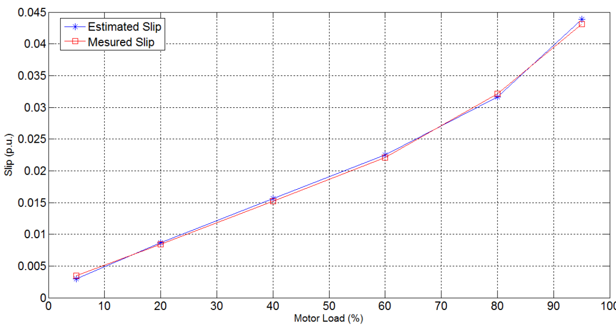

Fig.5. Comparison between the measured and estimated slip

B. *Frequency auto search*

After determining the slip, we want now to identify the frequencies and the magnitudes of the RBFH from the stator current spectrum. The easy solution that can flash in mind is based on using, directly, the estimated slip to compute the frequencies of the target harmonics (via their expression (2)) then deducing their magnitudes. However, with this solution, any small error on the slip estimation can lead to a false identification of the RBFH. For example, Fig.6 shows that an error of $E_{slip} = 2.38\%$ on the slip estimation causes a slight error of $E_f = 0.22\%$ on the frequency localization of the $(1-2s)f_s$ component, but it causes a large error of $E_A = 70.9\%$ on the amplitude identification.

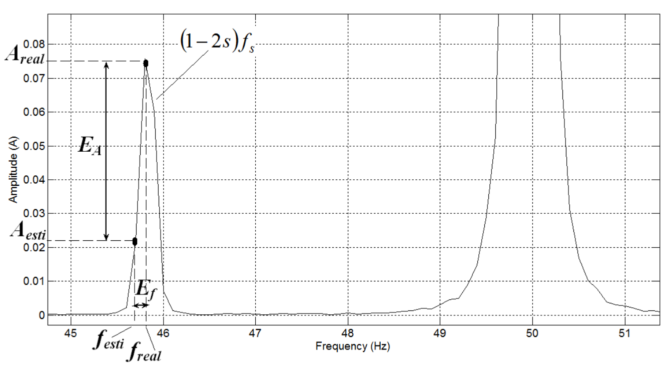

Fig.6. Errors on the Amplitude and frequency identification

The best way to avoid this big problem is to define a searching interval corresponding to each harmonic. This interval is defined as follows:

$$searching\ Interval = \left[f_{esti} - n_1.\Delta f ,....., f_{esti} + n_2.\Delta f \right] \qquad (11)$$

Where f_{esti} is the frequency of the target harmonic, obtained via the estimated slip (using its own expression frequency (2)), Δf is the frequency resolution, n_1 and n_2 are integers. These integers define the length of the searching interval. Therefore, the component which has the highest magnitude in this interval, surely has the real frequency and the real amplitude of the desired harmonic.

In order to verify the efficiency of our frequency auto-search algorithm, several tests are carried out under various loads; one of these tests is presented on Fig.7. As can be clearly seen, the amplitudes and the frequencies obtained from the proposed frequency auto-search algorithm coincide perfectly with the real coordinates of searched harmonics. In addition, this algorithm has successfully determined the coordinates of other spectral components (TH, RSH and EFH) with a very high precision; which makes it an important tool that can be used in other application related to the advanced processing signal.

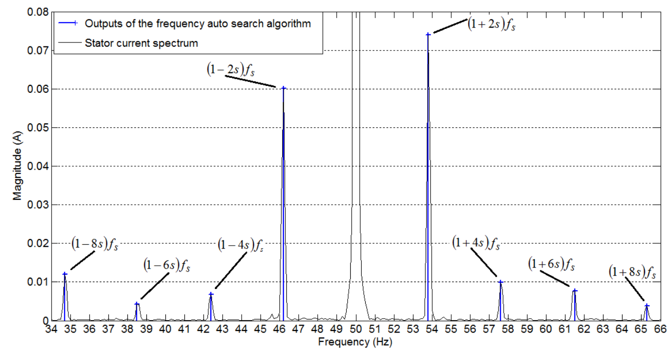

Fig.7. Test of the frequency auto search algorithm

C. *Computing Algorithm of the RHI*

We want now to calculate the RHI_{RBFH} by using (5). It is obvious that we require the RBFH amplitudes. As demonstrated previously, the proposed frequency auto search algorithm allows us to identify these amplitudes, but since the RBFH is an infinite series of spectral components, it is impossible and unnecessary to find all their amplitudes. Thus, we limit this study to the spectral components presented on Table II.

TABLE II. THE CANDIDATE RBFH

Harmonic type	The candidate spectral components
RBFH	$\left(\{v = 1,3,5,7\} \pm 2\{k = 1,2,3,4\}s\right)f_s$

Among these candidate harmonics, only the most sensitive components will be selected to compute the RHI_{RBFH}. This step has a crucial importance because the efficiency of the proposed fault detection algorithm depends strongly on the choice of the spectral components used to generate the RHI.

The selection process is performed by evaluating the CI (calculated using (4)) associated to each harmonic listed in Tab.II. It means that the candidate spectral components of an actual current spectrum, must be compared with those of a reference spectrum. This operation demonstrates the need for learning the amplitudes of the RBFH of the healthy motor (taken as a reference) in order to reliably calculate the CI for a wide operating range. However, these amplitudes vary with the operating load, which represent a problem that must be resolved.

On this direction, it is known that the slip is the important factor that determines an operating condition for an induction motor. Consequently, it is possible to perform a few numbers of tests with healthy machine under representative operating conditions. For each test, the slip and the required amplitudes can be determined and stored in a two-dimensional table. Afterwards, some techniques can be used to interpolate and extrapolate the 2-D table to obtain the healthy information. This allows computing the CI associated to any spectral components for the entire operating range.

It is important to note that for certain applications, the used motors work always under same load (for example: always under rated load or medium…). Consequently, the generation of healthy information requires only some tests with this operating load when the motor is installed. The healthy information should be updated after all general revision.

In order to evaluate the CI related to the candidate harmonics, it is imperative to put a criterion which will help us to choose the most sensitive components that will be used to calculate the RHI. Note that a wrong choice leads to lose of useful information and consequently to a wrong detection. Therefore, the authors have defined the following criterion :

Only the spectral components that have a $CI \geq S$ will be used to compute the different RHI.

Where S allows setting the sensitivity degree of our fault detection algorithm, as follows:

TABLE III. THE USED VALUES FOR *S*

$S = 1.5$	Correspond to a High sensitivity
$S = 5$	Correspond to a Low sensitivity

For example, if $S = 1.5$, this implies that all harmonics that have increased more than 50% ($harmonic\,Increase(\%) = (S-1)\times 100$), contribute to the information given by the RHI. In this case, if there are spectral components that meet with the defined criterion, the obtained RHI_{RBFH} will be equal or superior to 1.5.

Therefore, S has a crucial importance; it can be regarded as a threshold from which we report the existence of a defect. It can also have other values than those presented on Tab. III. A small value for S means that the fault detection algorithm will react to any little variation on the RBFH's amplitudes.

D. Classification and Normalization of the RHI

On the monitor screen of the personal computer, used as an interface of the diagnosis system, the results must be displayed in a manner that allows separating between the healthy and faulty states. For that reason, the values of the RHI_{RBFH} are classified and normalised. The authors have defined three intervals corresponding to three normalised values (Tab.IV):

TABLE IV. THE CLASSIFICATION INTERVALS AND THE NORMALISED VALUES OF THE RHI_{RBFH}

	RHI_{RBFH}	Normalised Values	Displayed Color
Interval I	$RHI_{RBFH} \leq S$	1	Green (G)
Interval II	$S < RHI_{RBFH} \leq 5S$	2	Orange (O)
Interval III	$RHI_{RBFH} > 5S$	3	Red (R)

As shown on Tab.IV, the intervals boundaries depend strongly to the sensitivity degree *S*.

If RHI_{RBFH} belongs to the *Interval I*, means that there is no spectral component that meets with the defined criterion. In this case, the value 1 will be imposed to the corresponding RHI. As a result, for a motor working under normal conditions and healthy state, the RHI_{RBFH} will be equal to 1 and the color Green will be displayed on the monitor screen.

If RHI_{RBFH} belongs to the *Interval II*, this signifies that there are important increases on the RBFH. The magnitudes of these harmonics can raise about four times bigger than their healthy values. In this case, the RHI_{RBFH} takes the normalised value 2, and the color Orange will be displayed on the monitor screen. Consequently, the user can easily state the existence of a rotor fault.

When RHI_{RBFH} belongs to the *Interval III*, the normalised value 3 will be imposed and the color Red will be displayed on the monitor screen. This warns the user of a severe rotor fault.

VI. EXPERIMENT OF THE PROPOSED ALGORITHM

The main goal of this section is to illustrate the efficiency of the proposed algorithm to detect rotor faults in a 3kW three-phase induction motors.

First, few experiments are performed on this motor at healthy state under low, medium and high loads. For each experiment, the slip and the magnitudes of the candidate RBFH (Tab.II) are determined and stored. This operation is done just once every time we change the motor type, and it permits the automatic generation of the healthy information.

Afterwards, seven sets of experiments are carried out on this motor with different states (healthy and with one broken bar) and under various loads. Each experiment contains four tests; the details of these tests are presented in Tab.V.

TABLE V. THE EXPERIMENT DETAILS

Experiments		Details
The sets	**Acquisition Number**	
Set 1	From 1 to 4	Healthy motor, under 20% of rated load
Set 2	From 5 to 8	Healthy motor, under 50% of rated load
Set 3	From 9 to 12	Healthy motor, under 100% of rated load
Set 4	From 13 to 16	With one broken bar, under 100% of rated load
Set 5	From 17 to 20	With one broken bar, under 60% of rated load
Set 6	From 21 to 24	With one broken bar, under 20% of rated load
Set 7	From 25 to 28	With one broken bar, under 10% of rated load

For each test, the stator current is acquired then it is injected into the proposed algorithm. Fig.8 shows the algorithm interface displayed on the monitor screen of the personal computer. A simple click on the '**Start**' button allows running the main algorithm and displays the RHI_{RBFH} corresponding to each data-acquisition.

As can be clearly seen, the obtained results reflect perfectly the details illustrated in Tab.V. According to the RHI_{RBFH} values, the user can easily confirm that the first twelve tests correspond to a healthy motor, while the other tests correspond to a motor with rotor fault. Consequently, one can note that the separation between the healthy and faulty conditions becomes fast and more easy. It is to be noticed that the proposed algorithm has successfully detected the occurrence of rotor fault even under very low load (the last four tests), which demonstrates the accuracy and the robustness of our algorithm.

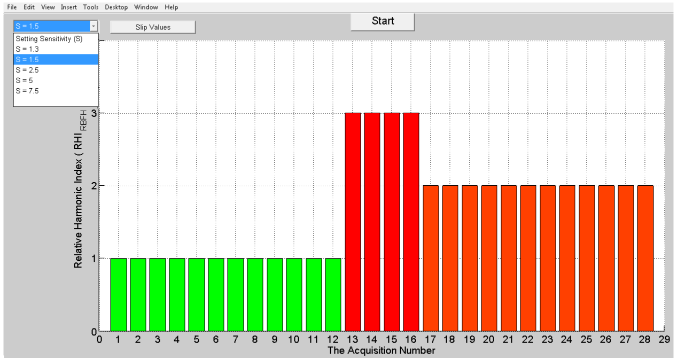

Fig.8. The RHI corresponding to the experiments described in Tab.V

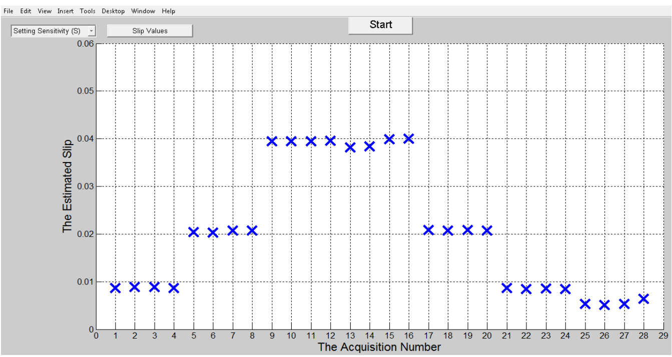

Fig. 9. The estimated slip for the experiments of Tab.V

The algorithm interface (Fig.8) allows the possibility to change the sensitivity degree to the desired value, via the Pop-up menu '**Setting Sensitivity *S***'. In addition, the slip corresponding to each test, can be easily obtained by a simple click on the '**Slip Values**' button. Consequently, we obtain Fig.9.

VI. CONCLUSION

This paper has proposed an improved fault detection algorithm dedicated to ameliorate the reliability of the fault detection task. This algorithm is based on monitoring of a new fault indicator called Relative Harmonic Index (RHI). As inputs, this algorithm needs only the stator current signal; it has undergo a lot of experimental tests and the obtained results have demonstrated its effectiveness to detect rotor fault in induction machines even at very low load. It was shown that the proposed algorithm allows the user to know the motor state, the fault severity and the slip corresponding to any data acquisition.

Compared to other fault detection strategies, based on pattern recognition or neural network, the proposed fault detection algorithm does not need to make a lot of tests, only a few tests with a healthy machine and under some different loads are required. These represent an important advantage which gives a good appreciation to our strategy and can provide it an advanced place among the other fault detection strategies.

REFERENCES

[1] C. Bruzzese, "Analysis and Aplication of particular Current Signatures (Symptoms) for Cage monitoring in Nonsinusoidally Fed Motors With High Rejection to Drive Load, Inertia, and Frequency Variation," *IEEE Trans. On Ind. Elect.,* vol.55, no.12, pp. 4137-4155, Dec. 2008.

[2] T. J. Sobczyk and W. Maciolek, "Dose the Component $(1\text{-}2s)f_0$ in Stator Currents is Sufficient for Detection of Rotor Cage Faults," in *Proc.* SDEMPED'05, pp., 2005.

[3] J. H. Jung, J. J. Lee and B. H. Kwon, "Online Diagnosis of Induction Motors Using MCSA," *IEEE Trans. On Ind. Elect.,* vol. 53, no. 6, pp. 1842-1852, Dec. 2006.

[4] W. T. Thomson and M. Fenger, "Current Signature Analysis to Detect Induction Motor Faults," *IEEE Ind. Appl. Mag.*, vol.7, no.4., pp. 26-34, Jul./Aug. 2001.

[5] A. Bellini, F. Filippetti, C. Tassoni and G. A. Capolino, "Advances in Diagnostic Techniques for Induction Machines," *IEEE Trans. On Ind. Elect.,* vol. 55, no. 12, pp. 4109-4126, Dec. 2008.

[6] P. Zhang, Y. Du, T. G. Habetler and B. Lu, "A Survey of Condition Monitoring and Protection Methods for Medium-Voltage Induction Motors," *IEEE Trans. On Ind. Appl.* vol. 47, no. 1, pp. 34-46, Jan/Feb 2011.

[7] F. Filippetti, G. Franceschini, C. Tassoni and P. Vas "AI Techniques in Induction Machines Diagnosis Including the Speed Ripple Effect," *IEEE Trans. On Ind. Appl.* vol. 34, no. 1, Jan/Feb 1998.

[8] G.R. Bossio, C. H. De Angelo, "Evaluation of Harmonic Current Sidebands for Broken Bar Diagnosis," in *Proc.* SDEMPED'09, pp.1-6, 2009.

[9] S. Choi, B. Akin, M. M. Rahimian and H. A. Toliyat, "Implementation of a Fault-Diagnosis Algorithm for Induction Machines Based on Advanced Digital-Signal-Processing Techniques," IEEE Transactions on Industrial Electronics, vol,58, pp.937-948, 2011.

[10] I. Aydin, M. Karakose, E. Akin, "A New Method for Early Fault Detection and Diagnosis of Broken Rotor Bars, Energy Conversion and Management," vol.52, pp. 1790–1799, 2011.

BIOGRAPHIES

Mohamed Sahraoui received the Engineer, "Magistère" and "Doctorat en Science" degrees in electrical engineering from the University of Biskra, Algeria in 2001, 2003 and 2010 respectively. He is interested in the modelling, condition monitoring and faults diagnosis of electrical machines. Mr. Sahraoui is an assistant professor with the University of Constantine, Algeria since 2005 and he is a member in the LGEB Laboratory

Salah Eddine Zouzou received the B.S degree from the "Ecole Nationale Polytechnique d'Alger", Algeria in 1987 and the M.S and Ph.D degrees from the "École Nationale Polytechnique de Grenoble" France, in 1988 and 1991 respectively. His fields of research interests deal with the design and condition monitoring; of electrical machines. Prof. Zouzou is an associate Professor at the University of Biskra, Algeria and he is the director of the LGEB Laboratory since 2004.

Adel Ghoggal became Electrical Engineer from the University of Biskra, Algeria, in 1996. In 2005, he received the "Magistère" degree in electrical engineering from the University of Batna, Algeria and the "Doctorat en Science" degree from the University of Biskra in 2010. Mr. Ghoggal is an assistant professor with the University of Constantine, Algeria since 2005 and currently, he is a member in the LGEB Laboratory.

Salim Guedidi received the D.E.S from the university of Batna, Algeria and the D.E.A from the university of Nancy, France. He is interested in the modelling, condition monitoring and faults diagnosis of electrical machines and working toward the Ph. D degree on the same axis. Mr. Guedidi is an assistant professor with the University of Biskra and he is a member in the "Laboratoire de Génie Electrique de Biskra.

Derghal Hamid received the engineering degree on electrical engineering from University of Batna in 1988 and the "Magistère" degree from the university of Biskra-Algeria in 2000. Now he working toward his "Doctorat en Science" on signal processing and fault detection. Mr. Derghal is an assistant professor with the University of Biskra and he is a member in the "Laboratoire de Génie Electrique.