Study of the startup transient for the diagnosis of broken bars in induction motors: A review

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Abstract- The aim of this paper is to develop a review of the different hitherto proposed methods, that are based on the analysis of currents for the diagnosis of rotor failures in induction motors. Firstly, the paper focuses on the classical methods, based on the study of currents in steady state, which have been deeply studied during the last years. Afterwards, some new approaches that are based on the study of the transient processes of the machine are analysed, mainly those focused on the study of the current during the startup. In this sense, it is specially remarked a new approach recently introduced by the authors for the diagnosis of rotor bar breakages through the analysis of the startup current using the wavelet theory. The advantages of this alternative approach are discussed in the paper showing the interest of this method.

Keywords: Broken rotor bars, startup transient, fault diagnosis, wavelet analysis.

1. Introduction

Traditional methods for the diagnosis of broken rotor bars in induction machines have been mainly based on the study of the stator currents in steady-state. The tracing of two harmonic components placed around the fundamental frequency - sideband components - constitutes the basis of such methods, having demonstrated in a wide range of cases very interesting results for the diagnosis of bar breakages in induction machines. In addition, the amplitude of those components have served as a basis for the elaboration of several diagnosis indexes for the quantification of the severity of the fault. Nonetheless, the analysis in steady-state involves some disadvantages that make it not suitable when it is applied in some cases such as unloaded or light-loaded machines or when frequencies close to those caused by the broken bars appear due to different causes such as oscillating torque loads, voltage fluctuations or bearing faults.

In this context, during the last few years several new methods, based on the study of the startup transient current, have been developed. These new approaches have shown the validity of the study of that transient for diagnosing the presence of rotor bar failures in induction machines or for complementing the information provided by the classical methods, focused on the analysis of the currents in steady-state. These new approaches, like the classical ones, are no invasive. But, in addition, they avoid some of the disadvantages that the application of the traditional approaches implies.

In this sense, the mathematical tool used for the analysis plays a crucial role, since it must be suitable for the study of non-stationary processes. Thus, some recent works [1-3] have proposed the Wavelet Transform as a valuable tool for performing this analysis due to its inherent advantages.

In Section II of this paper it is performed a review of the different aspects, concerning the analysis of currents in steady-state, that have been investigated during the last few decades. In Section III some new methods, proposed by different authors, based on the analysis of transient processes in the machine are commented. Finally, in Section IV, it is remarked a new diagnosis method focused on the analysis of the startup stator current by means of the Wavelet Transform, which has recently been proposed by the authors.

2. Methods based on analysis in steady-state

During the 70's, a generalized field theory [4] was used in order to show that the presence of asymmetries in both members of an induction machine led to the induction of currents with an infinite sequence of frequencies [5]. It was also shown that, if that asymmetry took place in the rotor winding, there were finally induced certain characteristic frequencies in the stator current. [6] confirmed those considerations and showed that it was possible to detect the presence of broken bars through the examination of the currents and vibrations spectrums. The idea proposed by Hargis consisting of monitorizing the current was proved to be a reliable method to diagnose the presence of broken bars in the machine [7].

Following the approach introduced later by Deleroi [8], the effect of a bar breakage can be decomposed as the superposition of two configurations; the machine in healthy state plus the machine with a current source flowing through the broken bar, with a value equal to the current in healthy conditions but with opposite sense, giving the sum a null current though the considered bar.

The effect of the breakage can be then analysed studying the air-gap field that this second configuration produces (fault field). This is a fixed-axis non-sinusoidal field with two pair of poles that pulsates at the slip frequency and with its maximum value placed at the position of the broken rotor bar. It can be decomposed using Fourier theory as a sum of infinite sinusoidal fields with different frequencies. Each one of those fields can be decomposed by means of the Leblanc theorem in two fields rotating respect to the rotor at their pulsation frequency; one in direct sense and the other in opposite sense. Some of these field components will induce (depending on the constructive characteristics of the machine) some current components in the stator winding [9, 10].

Among these current components, the must relevant are those which are induced by the components of the fault field with p pole pairs (p is the number of pairs of poles of the machine). These components are known as (left and right) sideband harmonics and their frequencies are given by (1), as it was introduced in several works by Kliman, Elkasabgy, Thomson and others [11-14].

$$f_b = (1 \pm 2 \cdot s) \cdot f \qquad (1)$$

where s is the slip and f is the supply frequency.

These harmonics are already present in the machine in healthy state due to asymmetries, imperfections caused by the fabrication process and other constructive characteristics of the machine. But, in the case of a rotor bar breakage, their amplitudes are significantly increased.

More concretely, as it was remarked in some of the works mentioned, the left sideband component $(1\text{-}2\cdot s)\cdot f$ is specifically due to the fault field, whereas the right sideband component $(1+2\cdot s)\cdot f$ is due to the consequent speed oscillation caused by the previous one. In fact [15] showed that the presence of broken bars was the origin of a sequence of sideband harmonics given by (2).

$$f_b = \left(1 \pm 2 \cdot k \cdot s\right) \cdot f \qquad k=1,2,3\ldots \qquad (2)$$

The amplitude of the left and right sideband components relative to the fundamental component has been used by several authors for diagnosing the presence of the breakage and for quantification purposes [9-11]. In those works some approximate values of these relations are given for different cases of fault that could serve as a reference for the diagnosis of the degree of severity of the fault.

In this sense, some authors like Bellini and others [14] or Thomson and others [16] showed that the amplitude of the sideband components is affected by the inertia of the machine and load , fact that need to be considered in order to elaborate an accurate fault diagnosis index. In [15] a new index was proposed in order to eliminate this influence.

In addition, the appearance of other high-order harmonics in the stator current due to the breakage was remarked by some authors like Kliman [11], Gaydon [17] and others. These components are induced by certain harmonic components of the fault field with order greater than p. The general expression of these components is given by (3).

$$f_b = \left((k/p)\cdot(1-s) \pm s\right) \cdot f \qquad (3)$$

where f_b: detectable bar breakage frequencies, k/p=1,3,5…

The study of these high order harmonics can constitute an important complementary diagnosis tool to be applied in cases when any phenomenon could make difficult the diagnosis if only the sideband components are used. These can be, for instance, the presence of interbar currents or the existence or load fluctuations [9]. In these cases the amplitudes and frequencies of the high-order harmonics are not so affected by these phenomenons as those of the sideband harmonics are. This fact indicates the possibility of using these harmonics for complementing the information provided by the sideband components. However, due to the dependence of their amplitude on the constructive characteristics on the machine, it is not possible to use them always, since their amplitude may not be high enough for being detected.

Authors such as Kerzenbaum or Landy [18-19] analysed the influence of those known as interbar currents. These are currents that circulate throughout the iron between neighbour bars. The presence of these currents, which are only specially important in large motors, makes more difficult the rotor bar breakage diagnosis since it softens the distortion caused by the breakage in the air-gap field.

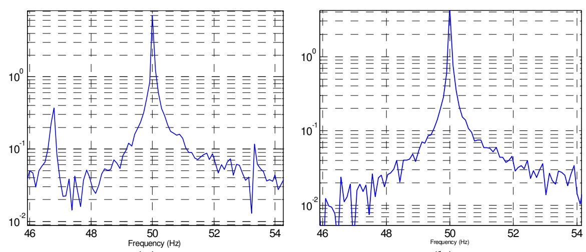
More recent works have developed methods based on modern artificial intelligence techniques such as neural networks, genetic algorithms or fuzzy logic for detection and quantification of rotor faults and, more concretely, bar breakages [20].

Even some investigators have ventured to create some devices which could diagnose the presence of broken bars in induction machines, being based their implementation on the classical theory, by means of the measure of the amplitude of the sideband components. In this sense, it can be remarked the device introduced by

Fenger and others [21], that could discriminate between different kind of faults.

Many other authors have deepened in the study of other aspects concerning this classical method for broken bar detection. However, some inherent problems of analysis in steady-state remain still unsolved.

Among the different disadvantages that the application of the classical approach implies, it can be remarked the impossibility of using it for the broken bar diagnosis in unloaded or light-loaded machines, since the sideband components overlap then the supply frequency (Fig. 1(b))

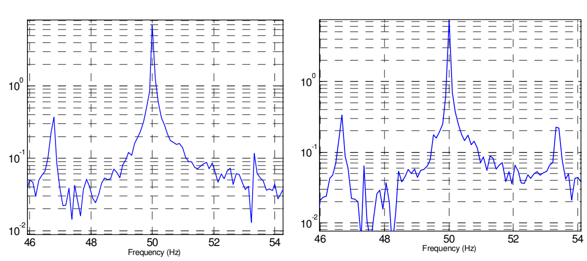


(a) (b)

Fig. 1. Classical detection of broken rotor bars. (a) loaded machine (b) unloaded machine

In addition, other faults different to broken bars (torque oscillations, ball-bearing defects, voltage oscillations…) can cause frequencies near to those introduced by the bar breakage, making difficult the diagnosis [1-2]. In fact, as it is shown in several works [9, 22] when pulsating loads are applied to an induction motor, the speed and torque oscillations cause alterations in the air-gap field and, thus, in the stator current. This is the case when the motor drives devices such as compressors, pumps and particularly mills and other machines with coupled gear reducers. In general, it can be said that any external cause capable to provoke fluctuations in the speed of the motor or, equivalently, in its torque, can cause the appearance of harmonics in the supply currents. The problem lies in the fact that these harmonics can have frequencies near to those associated to the sideband harmonics, fact that can create confusion and lead to a wrong diagnosis.

In Fig. 2 it can be seen the similarity between the frequency spectrum of a machine with two broken rotor bars (Fig. 2(a)) and that of a healthy machine with a fluctuating toque load.



(a) (b)

Fig. 2. (a) Sideband components due to broken rotor bars. (b) frequencies caused by fluctuating torque in a healthy machine

For instance, as it is shown in [9], gear boxes produce characteristic frequencies in the vibration spectrum of the machine, as well as torque oscillations as a result of the coupling between the different gears. Thus, it is common the occurrence in the currents spectrum of frequencies that are multiple of the known as rotating frequency of the gear box, that is, the frequency in Hz corresponding to the output speed of the gear box. This family of frequencies with the form $\pm K \cdot f_{rg}$, where f_{rg} is the rotating frequency at the output of the gear box, can be observed in the stator currents spectrum of the machine around the fundamental frequency.

In general, frequencies introduced by other phenomenon such as dynamic or static eccentricity or axis misalignment are far from those created by the bar breakage as it is shown in several works [9, 23-24].

On the other side, in some works [25] are remarked the difficulties that the analysis in steady-state involves when studying the outer-cage condition in double-cage rotors. As it is defended in those works, the outer-cage can be severely damaged without being detected the fault in stationary regime, due to the own characteristics of the analysis in steady-state, problem that perhaps could be solved by means of the study of the startup transient.

3. New approach: Analysis of the startup transient

These and other reasons caused the development of some methods focused on the analysis of the transient processes of the machine. [26], for instance, introduced a new approach based on the study of the stator voltages induced by the rotor flux, during the disconnection transient. From this work, if no broken bars exist on the machine this voltage is purely sinusoidal (except on if there are asymmetries inherent to the machine). If broken bars exist, there will appear certain components within the voltage frequency spectrum that can be used for diagnosing the fault. The proposed method presents, nevertheless, some disadvantages such as the fact that the amplitude of the spectral components depends on the disconnection instant, the short duration of the transient process or the difficulty to diagnose the presence of interbar currents when they exist.

But, it has been the study of the startup transient which has attracted the most attention, with regard to the diagnosis of rotor bars in induction machines. Among the first works in this field, should be remarked [27], although the signal analysis tools there employed, were not completely suitable for the study of transient signals such as the startup current.

A time-varying frequency spectrum was proposed in [28] for the study of the current during the transient. That spectrum, in a certain way, allowed the analysis of the spectral components during the startup in order to detect a possible pattern in their evolution. However, the frequency resolution was not high enough, fact that turned into a difficult analysis of the resulting pattern.

More recent works began to employ techniques more adequate for the analysis of transient magnitudes. The aim of all these contributions was to detect the evolution of the left sideband harmonic during the startup transient, fact that could lead to detect and quantify the bar breakage in the machine. For this purpose, filtering techniques were proposed [25, 29], although a certain complexity on the methodology and high computational requirements were needed.

Some interesting contributions by those authors proposed the application of the Wavelet theory for the study of the startup current [3, 30-31]. The approach was based on the convolution of the startup current signal with a Gaussian wavelet, fact that is equivalent to filter the signal, extracting the components within the particular frequency band associated with that wavelet. A three-peak characteristic pattern was obtained from that convolution. Some remarkable conclusions were derived from those works by Watson and others, where it was highlighted the evolution of the characteristic harmonic associated to broken rotor bars during the startup transient. However, this evolution was analysed within a particular frequency band (from 20 to 30 Hz).

Despite this fact, those works supposed a clear advance, not only because they remarked the evolution of the left sideband harmonic during the startup, but also because in those works were given some quantitative values based on the results of transient analysis, which pretended to serve as reference for diagnosing the presence of broken bars in induction machines. In addition, they were one of the pioneers in proposing the use of the wavelet theory for the analysis of these kind of signals for the diagnosis of faults in induction motors.

As many authors have shown in different fields [32-35], wavelet theory have been proved to be a powerful tool for analysis of transient processes, providing some important advantages with respect to the classical signal processing tools, more suitable for study of stationary processes. That is the reason why several authors have started to deepen in the application of this tool for the study of the startup transient in order to facilitate the extraction of patterns which help to the diagnosis of the breakage.

Other interesting works, focused on the study of the wavelet coefficients, were presented by Pillay and other authors [36]. Their conclusions did not show, however, a clear pattern associated with rotor bars which could be explained by physical reasons.

A very recent contribution based on wavelet ridge was presented by Zhang and others [37]. This method, also based on the appearance of the harmonic component during the startup, was based on extracting the known as wavelet ridge. This can be seen as curves that join the local maximums in a time-scale wavelet decomposition. In other words, it can give an idea of the instant frequency variation of this harmonic during the startup.

4. New contributions from the authors

In this context, the authors of the present paper proposed recently a new method for detecting the presence of broken rotor bars in induction machines [1-2]. The approach was based on the application of the Discrete Wavelet Transform (DWT) to the startup stator current. Each wavelet signal resulting from the decomposition contains the components of the original signal that are included within the frequency band associated to that wavelet signal. Thus, if a breakage exists in the machine, the evolution of the left sideband component associated to broken rotor bars during the startup can be reflected in the high level wavelet signals resulting from the analysis of the startup current. As the slip changes during the startup transient, according to (1), the frequency of that left sideband component will also change; It will vary from 50 Hz at the beginning of the transient (s=0) to 0 Hz (s=0.5) and again to near 50 Hz at the end of the startup. In Fig. 3 it is shown the theoretical evolution of the frequency of this harmonic component during the transient.

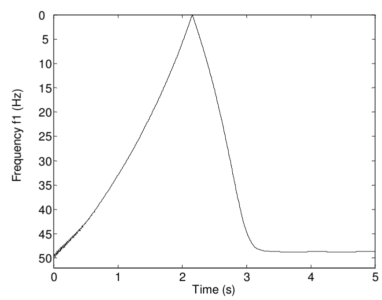
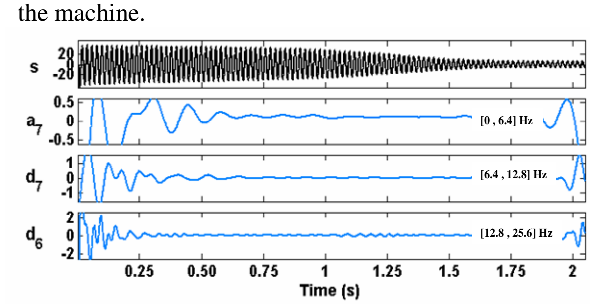
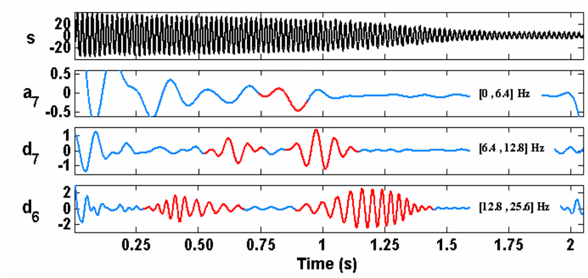


Fig. 3. Variation of the frequency of the left sideband during the startup process for a machine with a broken rotor bar.

Fig. 4 (b) shows the high-level wavelet signals (*a7*, *d7*, *d7*) resulting from the analysis of the startup current obtained experimentally for a machine with two broken rotor bars. The frequency bands associated to each wavelet signal are displayed beside their corresponding signal. There can be seen that those signals show a variation that fits with the frequency evolution of the left sideband component shown in Fig. 3. In addition, these signals can also reflect the variation in amplitude of that left sideband harmonic during the startup. Fig. 4 (a) shows the DWT decomposition for a healthy machine. There it can be seen that no variation is observed on these signals since the left sideband component has not an important magnitude because no broken bar is present on the machine.



(a)



(b)

Fig. 4. (a) High-level wavelet signals resulting from the DWT for a healthy machine. (b) High-level wavelet signals resulting from DWT for a machine with 2 broken rotor bars

All these results show the validity of the method for discriminate between a healthy and a faulty machine. Moreover the method provides satisfactory results even if it is used for the diagnosis in unloaded or light-loaded machines. It also allows a correct diagnosis of the fault although causes such as those mentioned above (torque load oscillations, bearing faults…) are present on the machine [2].

It can also serve as a basis for quantification purposes, as is being studied in current researches. The use of the approximation signal as an alternative medium to reflect the evolution of the harmonic and to facilitate the quantification of the severity of the fault is also being investigated by the authors.

5. Conclusions

A review of the state of art in the field of broken bar diagnosis in induction machines through the current analysis is presented in this paper. Firstly, the classical approach based on the study of the sideband components is described, performing a review of the different considerations done by different authors regarding that approach.

Afterwards, disadvantages of analysis in steady-state are commented, being specially remarked the case of presence of pulsating torque. Then, the methods introduced up to date that focus on the analysis of the startup current are described. In this context, it is emphasized the suitability of the wavelet theory for the study of transient signals such as the startup stator current.

Finally, a new method introduced recently by the authors for the diagnosis of broken rotor bars in induction machines is remarked, showing its validity for being applied in some cases where the classical approach does not provide so satisfactory results.

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