Detection of Broken Rotor Bars in Induction Machines through the Study of the Startup Transient via Wavelet Decomposition

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Abstract - **This paper introduces a new method for the diagnosis of rotor bar breakages in induction machines based on the application of the Discrete Wavelet Transform (DWT) to the startup stator current. Firstly, an explanation of the physical basis of the phenomenon is given; It is remarked the occurrence of a stator current harmonic with a particular frequency variation during the startup process, when a rotor bar breakage has happened. Afterwards, it is introduced a method for detecting this harmonic by means of the DWT. This method is based on the characteristic pattern produced by the harmonic on the high-level wavelet signals resulting from the startup current decomposition. This pattern is illustrated using a numerical model of an induction machine which allows the simulation of the startup process of a machine in healthy and faulty conditions. Finally, the proposed method is experimentally tested using a laboratory machine which easily allows the operation under different fault conditions.**

Index terms – **Broken rotor bars, startup transient, fault diagnosis, wavelet analysis.**

I. INTRODUCTION

Diagnosis of faults in electrical machines has been mainly based on the study of magnitudes in steady-state such as currents or voltages [1]. In particular, classical detection of broken rotor bars in induction machines in steady-state is based on the analysis of currents in the frequency domain [2]. The most extended method in industrial applications consist in the tracing of two harmonic components placed around the main frequency component at distances $-2sf$ and $+2sf$ (sideband harmonics), where f is the frequency of supply and s is the slip. The amplitudes of these two harmonics are related to the level of asymmetry of the rotor winding. In addition to these two, there are other not commonly used harmonics that can help for the diagnosis of rotor faults. The main advantage of this method is the simplicity of the equipment and the calculations required to be used. Main disadvantage of the analysis in steady state is load-dependence since the amplitude of the current components depends on the load that is connected to the motor, making difficult to establish an amplitude that separates a healthy motor from a faulty one. Another problem of this method is that harmonics with frequencies similar to the ones that are used for the rotor bar breakage diagnosis, can be produced by different causes such as oscillating torque loads, gear boxes coupling, bearing faults or external noises. In addition to this fact, if the machine is unloaded, this method is unsuitable, since the slip will be approximately zero and the frequencies associated with broken rotor bars overlap the frequency of supply [3].

In this sense, the study of transient processes such as the startup or disconnection transients can be a very helpful tool for the detection of broken rotor bars and other kind of faults, avoiding the disadvantages of analysis in steady-state but maintaining its simplicity. Keeping the simplicity of equipment and procedures is important for the suitability of the approach for industrial applications, specially in the case of small and medium size machines. Some researches have been recently carried on in this field, appearing several methods based on the study of the current spectra during the startup transient [3] or the induced voltages in the stator windings during disconnection [4]. In particular, the analysis of the startup transient constitutes a very important source of information that can help to the broken rotor bar and, more generally, to the fault detection. During this transient, load-dependence is almost avoided and a diagnosis based on the time evolution of the machine magnitudes is allowed, rather than one focused on their values in a particular operation condition. This, obviously improve the ability for the discrimination between different kinds of faults, in comparison with the steady-state analysis based methods.

Special suitability of wavelet analysis for the study of transients [3, 5, 6], makes it a very good tool for the analysis of the electrical magnitudes during startup or disconnection of the machine, proven that traditional methods work better for stationary signal processing. Thus, Fourier transform, that has been used long for signal analysis, provides the frequency content of the signal that is being analysed. Despite its inherent advantages, the Fourier transform is not suitable for the analysis of non-stationary signals, along with the fact that time information is lost, giving only the frequency components of the signal. To face this disadvantages Short Time Fourier Transform (STFT) was introduced. The idea was to perform the Fourier analysis in windows that were located in time. Although it works well for a certain range of problems, the constant size of the window implies that the resolution in the whole domain is the same, making it not suitable for the analysis of signals with frequencies varying in a wide range.

The introduction of wavelets came to solve all these problems. The idea of scaling of the basis functions introduced by this theory, allows to perform the analysis in the time-frequency domain of all kind of signals, becoming a method suitable for the study of transients there where Fourier methods do not work so well.

Despite all this advantages, application of wavelets to the analysis of startup currents is not very extended yet. A new method of rotor bar breakage diagnosis, based on the application of the Discrete Wavelet Transform (DWT) to the startup stator current is proposed in this article. Section II develops a physical-based description of the phenomenon during the startup transient when there is a broken rotor bar. The appearance of a stator current harmonic with a particular frequency variation during the startup process is remarked. Section III introduces a method for detecting this harmonic by means of the DWT. This method is based on the characteristic pattern produced by this harmonic on the high-level wavelet signals of the current decomposition. A numerical model of an induction machine is used to illustrate this characteristic pattern, simulating the startup process in healthy and faulty conditions. Finally, in section IV the proposed method is experimentally tested using a laboratory machine which easily allows the operation under different fault conditions.

II. DESCRIPTION OF THE PHENOMENON

A rotor bar breakage produces a distortion in the air-gap field; when the induction machine works at steady-state, this distorted field induces voltage harmonics in the stator windings. The frequencies of these harmonics [1] are given by (1).

$$f_k = f \cdot \left[k - s(k \pm 1)\right] \qquad (1)$$

where f_k are these frequencies, $k = \upsilon / p$ (where υ is the index of the considered field harmonic and p is the number of pairs of poles), s is the slip and f is the fundamental frequency.

Some of these voltage harmonics produce a current harmonic in the stator windings, with their same frequency. For the diagnosis method here proposed, we will only take into account the main current harmonic (left sideband harmonic) obtained from (1), with k=1 and positive sign in the parenthesis. The frequency of this harmonic, in steady-state is calculated by (2).

$$f_{1+} = \left| f \cdot (1 - 2s) \right| \qquad (2)$$

Let us consider an enough long startup process. Initially, the stator currents are not a three-phase balanced system but, after a short time, the transient electromagnetic phenomenon finishes. From this time to the time when rated speed is reached, the machine behaviour can be approximated by a succession of stationary regimes, one for each speed. For every of these stationary regimes there is a left sideband current harmonic with frequency given by (2), using the slip that corresponds to the considered time.

As the slip s varies from a value equal to 1 at first to a value near zero in steady-state, the result is that the frequency for this harmonic (f_{1+}) varies from the fundamental frequency to zero and again to the fundamental frequency. This is shown next.

$$\begin{array}{ll} s = 0 & f_{1+} = 50\,\text{Hz} \\ s = 1/2 & f_{1+} = 0\,\text{Hz} \\ s = 1 & f_{1+} = 50\,\text{Hz} \end{array} \qquad (3)$$

The study of the time evolution of the frequency of this harmonic is the starting point of the method proposed in this paper.

Fig. 1 and Fig. 2 show the evolution of the stator current and the speed during the startup of a cage induction machine with 24 bars in the rotor, with one of them broken. These curves were obtained from simulation, using a physically based numerical model [7, 8] which calculates the air-gap field at every time taking into account the current and the position of each machine conductor.

From the speed data, it can be obtained the variation of the frequency f_{1+} during the startup process, arising the graphic shown in Fig. 3. There it is shown how the frequency varies from an initial value equal to the fundamental frequency (in this case 50 Hz) to zero and how it raises again to the fundamental frequency.

If we split the frequency axis into different bands, for instance those shown in Fig. 4, the intersection of the frequency graph with the limits of each band defines the time intervals during which the frequency of the left sideband harmonic belongs to the band. This is what will be shown by means of the wavelet analysis. The proposed diagnosis method is based on the identification of a characteristic pattern in the high-level signals of the DWT of the startup current. This characteristic pattern is due to the fact that energies of wavelet signals increase notably within the time intervals in which their bandwidth contain the frequency of the left side-band harmonic (f_{1+}).

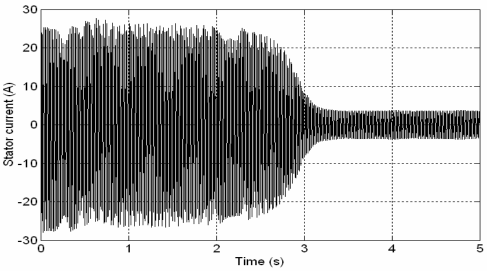

Fig.1 : Evolution of the stator current during a simulated startup in a machine with a broken rotor bar

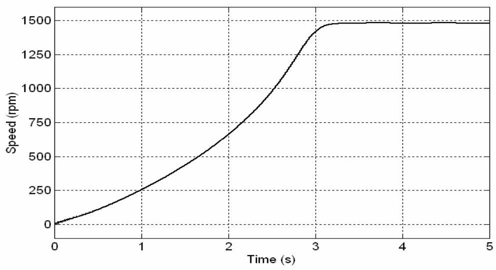

Fig.2 : Variation of speed across the simulated startup

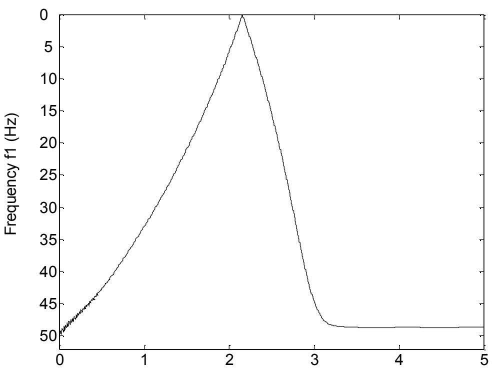

Fig. 3. Variation of the frequency f_{1+} during the startup process for a machine with a broken rotor bar.

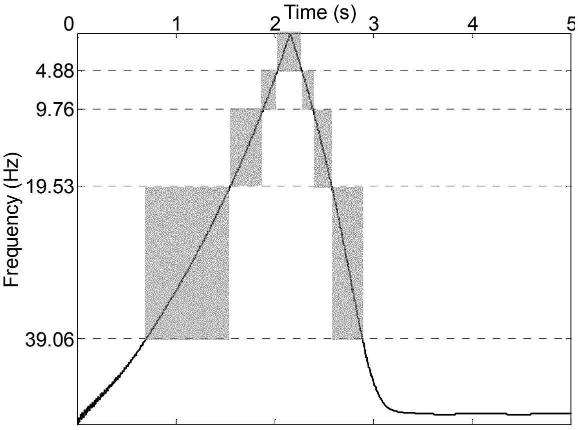

Fig. 4. Division of the frequency axis into frequency bands and definition of time intervals where frequencies must appear.

III. BROKEN BAR DETECTION VIA WAVELET ANALYSIS

Wavelet theory introduces the Discrete Wavelet Transform that is suitable for sampled signals. From this, it is deduced that every sampled signal s (s_1, s_2, …s_N) can be approximated by the sum of an approximation signal at a certain decomposition level n (a_n) and n detail signals (d_j with j varying from 1 to n) [9]. Each signal is the product of the corresponding coefficients (approximation coefficients for a_n and wavelet coefficients for d_j) by the scaling function or the wavelet function at each level respectively. This is shown in (3).

$$s(t)=\sum_i \alpha_i^n \cdot \varphi_i^n(t)+\sum_{j=1}^{n}\sum_i \beta_i^j \cdot \psi_i^j(t)=a_n+d_n+\ldots+d_1 \qquad (3)$$

Where α_i^n, β_i^j are the scaling and wavelet coefficients respectively, φ^n, ψ^j are the scaling function at level n and wavelet function at level j respectively, and n is the decomposition level. a_n is the approximation signal at level n and d_j is the detail signal at level j [10,11].

If f_s (samples/s) is the sampling rate used for capturing s, then the detail d_j contains the information concerning the signal components whose frequencies are included in the interval $[2^{-(j-1)}\cdot f_s\ ,\ 2^{-j}\cdot f_s]$ Hz. The approximation signal a_n includes the low frequency components of the signal, belonging to the interval $[0, 2^{-n}\cdot f_s]$ Hz [9,12].

Fig. 5 shows the DWT of the current in Fig. 1, while Fig. 6 displays the DWT of a simulation of startup stator current of the same machine and conditions but, in this case, without any broken bar. The decomposition was performed using Daubechies-12 as mother wavelet with n=7 levels; the sampling rate of signals was f_s= 1250 samples/s, determined by the time increment used in the resolution of the numerical model (Δt=0,0008 sec.). Table I shows the frequency band for each level.

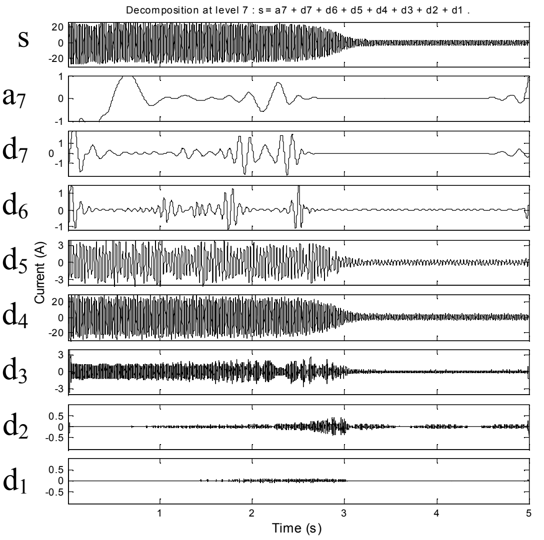

Fig.5: DWT of the simulated startup current (one broken bar)

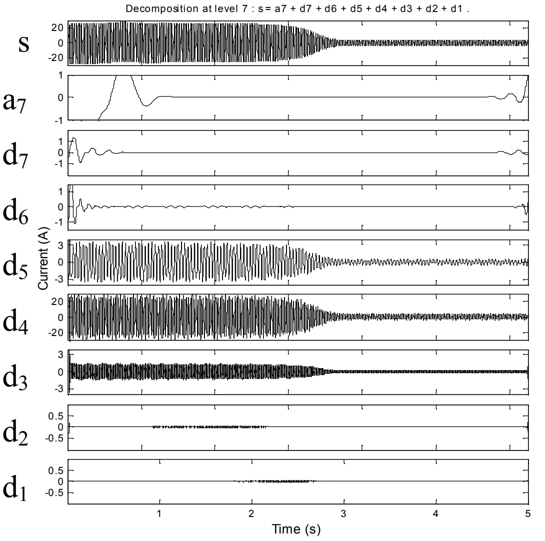

Fig.6: DWT of the simulated startup current (healthy case)

TABLE I
FREQUENCY BANDS AT EACH LEVEL

Level	Frequency band
d1	312.5 – 625 Hz
d2	156.2 – 312.5 Hz
d3	78.1 – 156.2 Hz
d4	39.06 – 78.1 Hz
d5	19.53 – 39.06 Hz
d6	9.76 – 19.53 Hz
d7	4.88 – 9.76 Hz
a7	0 – 4.88 Hz

Comparison between Fig. 5 and Fig. 6 clearly shows that the bar breakage can be identified by means of the “perturbations” that appear in the high-level signals of the decomposition (d_6, d_7, a_7). It is specially remarkable the fact that these “perturbations” into the wavelet decomposition of the faulty machine, can be physically explained as the signature of the left sideband harmonic across the startup transient: As the wavelet signals obtained from the wavelet analysis correspond to different frequency bands, the value of a wavelet signal at a certain moment informs about the presence in the analyzed signal of components whose frequencies belong to its frequency band.

Fig. 7 is a projection of the frequency bands displayed in Fig. 4 over the wavelet decomposition of the current for the faulty machine. It can be noticed in this figure how the energy of the wavelet signals corresponding to each frequency band below 50 Hz, that is, signals *d*5 to *a*7, shows a clear increase in those time intervals when frequency of the left sideband harmonic is included into the frequency band of the wavelet signal. The only exception is signal *d*5, where this trend is not appreciated so clearly. The reason is that other phenomenon causes the appearance of some frequencies within this band. Since these frequencies appear also for the healthy case we can conclude that these frequencies are not directly related with the broken bar phenomenon.

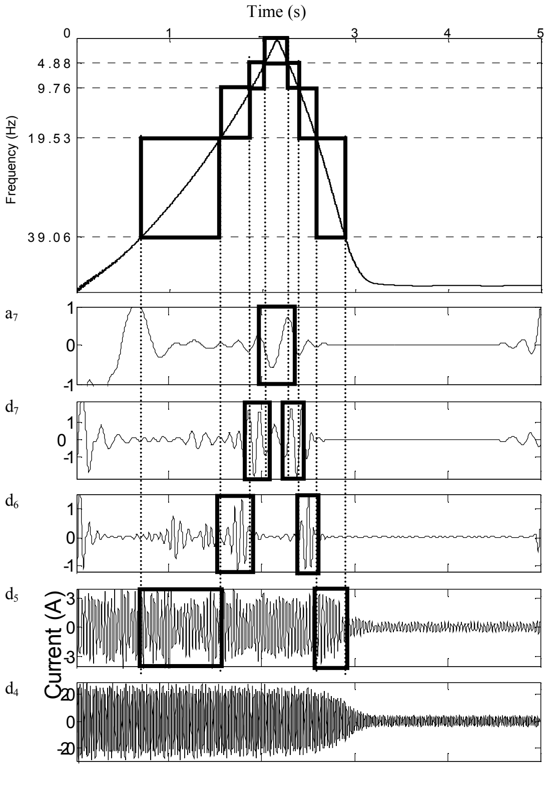

Fig. 7. Projection of the frequency bands during the startup process of a faulty machine over the wavelet signals

The previous physical assessments are important because relate the changes in the decomposition with the phenomenon that originates them. This allows the definition of a general pattern for characterization of bar breakages based on decomposition of startup current. This pattern does not depend on the DWT parameters or the machine characteristics and could be described as follows: Rotor bar breakages produce increases in the energy of the wavelet signals whose frequency bands are under the fundamental frequency. These increases of the energy are restricted to the time intervals arranged in this way:

- For the approximation signal a_n there is only one time interval with increase in energy; this interval is approximately centred at the time when the slip is equal to 0,5.
- For the detail of level n (d_n), there are two of those time intervals, placed on the left and on the right of a_n interval.
- For each detail d_{j-1} there are two of those intervals, placed on the left and on the right side of the intervals of the detail d_j.

The description of this pattern is a very helpful tool since it enables the bar breakage diagnosis, even if neither the decomposition signals of the stator current in healthy conditions nor the simultaneous speed register are available. In addition, this pattern can help to the discrimination between a bar breakage and other fault conditions which can also produce alterations in the wavelet decomposition, but with a different pattern.

IV. EXPERIMENTAL RESULTS

Experiments were developed using a laboratory machine with twelve accessible phases in its secondary winding, fact that allowed the simulation of several fault cases by means of the opening of these phases [13]. The characteristics of the machine were: Rated voltage (U_n): 240V, rated power (P_n): 1,25kW, 1 pair of poles, primary rated current (I_{1n}): 5A, rated speed (n_n): 2900 rpm and rated slip (s_n): 0,033.

Measures of the primary current during the startup transient were taken for the healthy case and for the cases with one to four opened phases that correspond to the case of two to eight broken rotor bars respectively. Data were obtained by means of an oscilloscope with a sampling rate of 819 samples/second.

Wavelet analysis of the data was performed using the MATLAB wavelet toolbox. After comparison between different types of mother wavelet, Daubechies-10 was finally adopted for the analysis. The results were similar for the different mother wavelets that were tested where it could be seen the effect of the broken bar over the wavelet signals corresponding to the different bands. In the end, Daubechies-10 was chosen because it showed clearly these features. In addition, 6-level analysis was performed since the most interesting frequency bands were included in such an analysis. It could have been used a wavelet packet analysis for a deeper study of the effect of the high frequencies in the phenomenon [9, 14], but this was out of the purpose of this work. Table II shows the frequency bands at each level for the wavelet decomposition of the experimental signals.

TABLE II
FREQUENCY BANDS AT EACH LEVEL

Level	Frequency band
d1	204.8 – 409.6 Hz
d2	102.4 – 204.6 Hz
d3	51.2 – 102.4 Hz
d4	25.6 – 51.2 Hz
d5	12.8 – 25.6 Hz
d6	6.4 – 12.8 Hz
a6	0 – 6.4 Hz

Fig. 8 shows the approximation and detail signals obtained from the wavelet analysis of the stator currents in healthy mode.

In Fig. 9 and Fig. 10 are plotted the signals resulting from the wavelet decomposition of the startup current in the case of one and four opened phases respectively. Oscillations at first of each signal are not considered since they are due to the electromagnetic transient and can be found either in healthy or faulty decompositions. While this transient occurs currents are out of balance.

Analysing the graphs when the electromagnetic transient is finished, it can be appreciated how the results are quite similar to those obtained from the numerical model. There is a clear difference between the current decomposition of the healthy and the faulty machines; in the graphs corresponding to the faulty machine are clearly observed increases in the energy of signals that fit exactly with the pattern described in the previous section. There can be seen how the wavelet signals with frequency bands below the fundamental frequency (that is, signals $d5$, $d6$ and $a6$) show energy increases during intervals arranged consecutively, in such a way that time intervals of the signal of level j are neighbor and are placed between the time intervals of level j-1. This pattern is produced by the continuous variation (first decreasing and later increasing) of the frequency of the left sideband harmonic during the startup.

This process could be also valid for the evaluation of the number of broken rotor bars, since the magnitude of the wavelet signal variation during the startup process is directly related with the number of rotor bars that break as can be appreciated in Fig. 9 and Fig. 10.

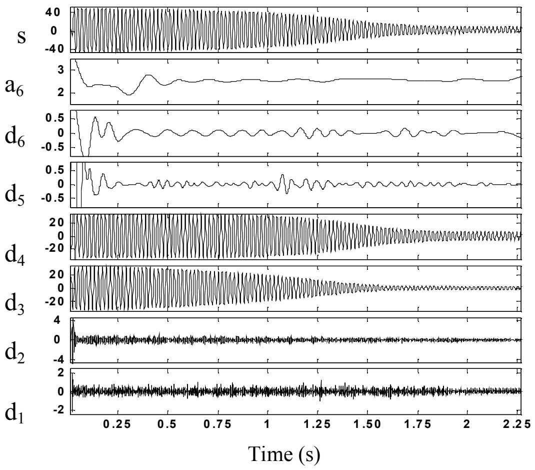

Fig. 8. 6-level wavelet decomposition using db-10 of current in healthy mode

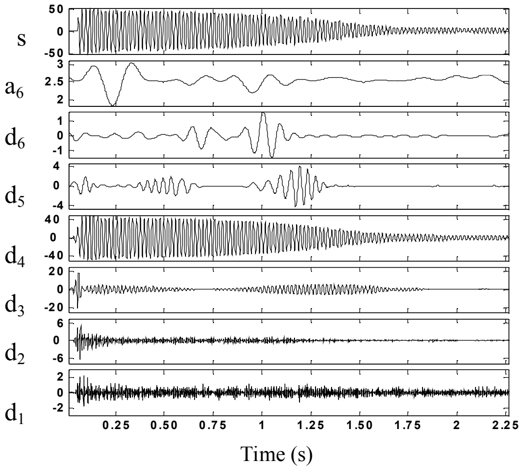

Fig. 9. 6-level wavelet decomposition of stator current in motor with an opened phase using db-10.

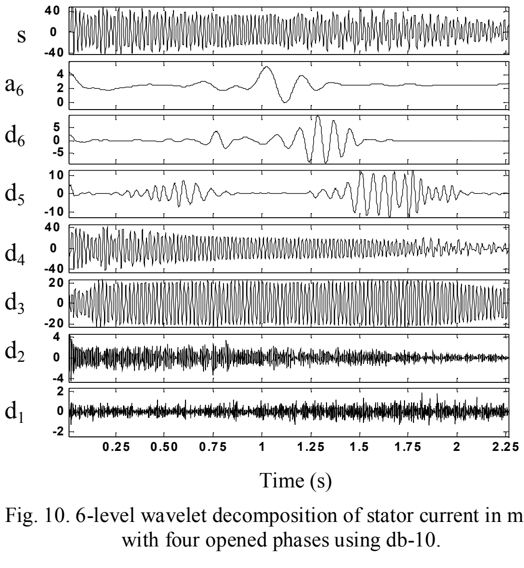

Fig. 10. 6-level wavelet decomposition of stator current in motor with four opened phases using db-10.

V. CONCLUSIONS

A new method of diagnosis of broken rotor bars in induction cage motors is proposed in this paper. The method is based on the analysis of the stator current during the startup transient, using the Discrete Wavelet Transform (DWT).

It is shown how rotor bar breakages produce a characteristic pattern in the wavelet decomposition signals. Firstly, this pattern is physically explained and afterwards it is verified both by simulation and by testing. The results show that this method has some important advantages in comparison with the classical approach, based on the stator current analysis in steady-state, such as less load dependence or the possibility of discrimination between different kinds of faults.

The most important limitation of the method lies on the fact that it is difficult to apply it to machines with a fast startup process, in which the duration of the transient electromagnetic phenomenon can not be neglected if compared with the total startup length.

Obviously, this method is not suitable for machines that are fed through frequency converters since, in these cases, the slip remains low during the startup process.

This work also shows that the Wavelet Transform is a mathematic tool that is very interesting for the methods based on the transient analysis, since it is specially suitable for the study of signals, such as the startup stator current, that have a spectrum which varies along the time.

Versus other methods focused on the analysis of the wavelet coefficients, analysis of wavelet signals offer a clear interpretation of the phenomenon. This makes easier the application of the method to different machines and startup conditions.

The results show great potential for the use of the method for predictive maintenance of electrical machinery. Future work will investigate a systematization method which serve as basis for the diagnosis of incipient faults and fast startup processes.

VI. APPENDIX A: DESCRIPTION OF THE TESTED MACHINE

The experiments were developed with an universal laboratory machine, whose windings were connected in order to obtain a squirrel-cage machine configuration.

The use of a laboratory machine has the advantage of making easier the development of the experiments and decreasing their cost. On the other hand, it has some constructive differences if compared with an industrial induction machine (the most important is that the secondary phases are winded instead of being simple bars).

In the test machine, the rotor winding is used as primary; it is made by three phases that are connected in triangle. The vertices of the triangle are connected to the network by means of three slip rings.

Fig 11 shows a cross section of the stator winding, which is used as secondary. As it can be seen, it consist in twelve short-pitch coils (10 slot pitch) with 66 turns/coil. Fig 12 shows the stator connections panel. The input (1, 2, 3) and output (1', 2', 3') endings of the stator windings are connected to the corresponding panel terminal. The figure also shows the connections to be performed to obtain an squirrel-cage-type winding with twelve phases. The connections between the upper or the lower terminals correspond to the short-circuit rings of an industrial machine. The characteristics of the resulting induction machine are: Rated voltage (U_n): 240V, rated power (P_n): 1,25kW, 1 pair of poles, primary rated current (I_{1n}): 5A, rated speed (n_n): 2900 rpm and rated slip (s_n): 0,033.

The switches connected in series with phases 2, 8 and 9 allow the simulation of the bar breakages. The tested conditions were:

- Healthy machine: All the switches closed.
- Two broken bars: Switch 2-2' opened, all the rest closed.
- Four broken bars: Switches 2-2' and 8-8' opened, 9-9' closed.

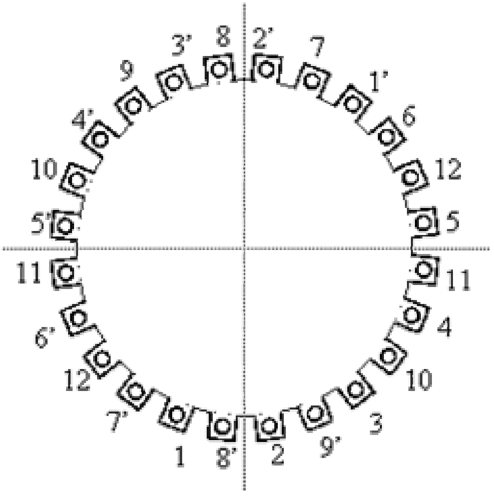

Fig. 11. Cross section of the stator winding of the machine.

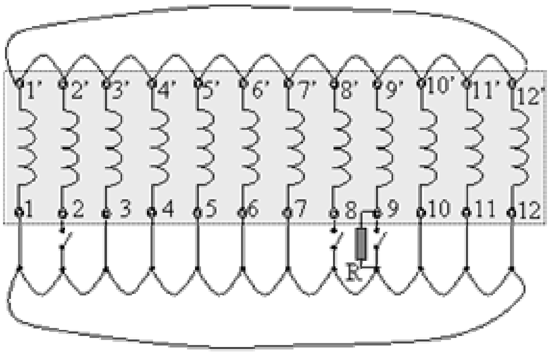

Fig. 12. Panel connection of the secondary winding of the tested machine.

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