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Influence of the start-up system in the diagnosis of faults in the rotor of induction motors using the Discrete Wavelet Transform

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Abstract

In previous articles, both the procedure and the advantages of the use of advanced mathematical tools,(as for example the Discrete Wavelet Transforms (DWT) and the continuous wavelet transforms (CWT)), for the time-frequency analysis of current signals captured in the stator during transients of starting and stopping have been deeply justified. The purpose of this analysis is the detection of rotor asymmetries as well as of possible eccentricities in induction motors. This article aims to analyze, from a qualitative point of view, the influence of the starting system on the results of the diagnosis method based on the analysis of the start-up current by using the DWT. Likewise, emphasis made on the impact and influence in the Wavelet Analysis (either through DWT or CWT) of harmonics introduced by the network, the motor itself and the possible fluctuations in the load torque. The results demonstrate the validity of the method, which presents a great robustness, regardless of the starting method or operating conditions. The theoretical conclusions were supported by actual measurements obtained in laboratory motors.

Keywords: Induction motors; fault diagnosis; transient analysis; wavelet transforms; start-up current

1. Introduction

The diagnosis of failures caused in the rotor of induction motors, by means of the analysis of transient currents through advanced time-frequency decomposition tools (TFD) has been a trend in recent years, mainly due to its advantages over the classic method known as Motor Current Signature Analysis (MCSA)[1-7].The analysis using the new method can avoid misdiagnoses (false positives and false negatives) that can occur when applying the MCSA. The new method enables to follow the evolution when present, of the characteristics components of the time-frequency maps and identify the associated patterns. These patterns are very unlikely to be produced by another type of phenomena, which confers great reliability to the method. Some of the harmonics induced in the stator winding currents by the air-gap field caused by the rotor failure have some characteristic frequencies whose values (and amplitudes) depend, among other, on the constructive parameters of the engine, the loading conditions and the inertia of the motor along with the load that the motor drives.

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The components related to asymmetries in the rotor that are usually employed in the industrial environment are given by the following expressions:

$$f_{b1} = (1 \pm 2ks)f, \quad k = 1, 2, 3 \ldots. \tag{1}$$

$$f_{b2} = \left[\frac{k}{p}(1-s) \pm s\right]f, \quad \frac{k}{p} = 1, 3, 5 \ldots. \tag{2}$$

As observed, the first family of components (*b1*), appears at both sides of the fundamental frequency *f*; these components show decreasing amplitudes when *k* increases.
The diagnosis is mainly focused on these components with low frequencies and, more specifically, on the left side harmonic (LSH) (component obtained for *k*=1 and negative sign in expression (1)), as it tends to have greater amplitude than the right one (*k*=1 and positive sign in (1))[10]. In addition, the amplitude of the LSH is usually much greater than that of the high order harmonics (high values of *k* in the second family), whose amplitudes are conditioned by motor winding characteristics, becoming in some cases almost impossible to discern them[11].

Basically, the transient analysis is based on identifying the evolutions (both on time and frequency) of the fault-related components during the considered transient regime; in this sense, it has been found that the detection of the evolution of the LSH during the transient start-up is particularly informative to clarify the presence of the fault. During that transient, the evolution of this component will follow a characteristic pattern with "Λ" shape in the time-frequency plane. This is due to the evolution of the frequency of this component as the slip *s* changes; in a direct-on-line start, the frequency of the LSH takes values from 50 Hz (when *s*=1) to 0 Hz (when *s*= ½) and again to near 50 Hz, when the permanent regime is finally reached; this leads to the emergence of the aforementioned failure pattern characteristic in any time-frequency representation of the start-up current (as for instance, the wavelet signals obtained from the DWT of that current)[1-2].

On the other hand, there are also other components related to rotor eccentricities. The most common is the case of mixed eccentricity (i.e. a combination of static and dynamic pure eccentricities). These mixed eccentricities result in the appearance of low frequency components[14], which according to various authors[17], are given by the following expression:

$$f_{ecc} = f\left[1 \pm m\frac{1-s}{p}\right], \quad m = 1, 2, 3, \ldots \tag{3}$$

The most relevant components are obtained for *m/p*= 1. The frequencies of these components also change with the slip, as the start-up takes place. Hence, it is also possible to identify these evolutions with the time-frequency analysis of the start-up current; this can be done, for instance, using the DWT that yields to an increase in the amplitude of the approximation signal and certain wavelet detail signals around that containing the fundamental frequency[2].

There are a wide variety of TFD tools to carry out the analysis of starting current in addition to the DWT and the CWT, such as the Hilbert Huang Transform, or Choi-Williams Wigner Ville Distributions etc…Experience has shown that the DWT has shown an excellent choice because of its simplicity, general availability in many software packages and computational speed, among other advantages. The DWT acts as a band-pass filter which decomposes the analysed signal (for instance, the start-up current) in a group of signals, each associated with a particular frequency band[1,8]. These signals allow visualizing the evolution of the different components present in the analysed signal, with velocity and simplicity. There are other alternatives, such as the continuous transforms, which provide a more accurate representation and clear of the evolution of the signal in the t-f map, enabling to follow the evolutions of high and low frequency components simultaneously. This advantage is especially interesting to detect components associated with multiple failures[9]. However in general terms, the computational burdens are much higher than those required with the use of the DWT.

In this paper, the results are obtained with an experimental test bench (Fig. 1) that enabled to perform different types of start, such as direct on line start, star-delta start, start by stator resistances and start via soft starter endowed with voltage ramp and current limitation. The test bench also features the necessary automatisms for the simulation of fluctuating load torques and different systems for coupling to the load (which in this case is a DC motor).The signals of the stator starting currents both of healthy induction motors and motors with forced bar breakages were captured using an oscilloscope at a sampling frequency of *fs*= 5 kHz. The general characteristics of the motors and the frequency bands, which reflect the evolution of the LSH (known *fs*), are shown in Tables I and II.

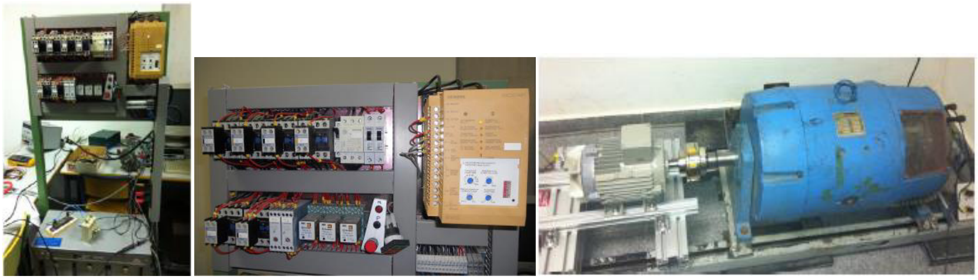

Fig.1. (Left) test bench to perform the different startups. (Right) 1.1 kW induction motor coupled to the D.C. load.

TABLE I
RATED CHARACTERISTICS OF THE 1.1 KWMOTOR

Rated Power	1.1 kW
Rated frequency	50 Hz
Rated Voltage	400 V
Rated primary current	2.7 A
Rated speed	1410 rpm
Rated slip	0.06
Connection	Star
Number of pole pairs	2
Number of rotor bars	28

TABLE II
FREQUENCY BANDS COVERED BY HIGH LEVEL DWT SIGNALS

Wavelet signal	App. Frequency band
a_8	[0~9] Hz
d_8	[9~19] Hz
d_7	[19~39] Hz
d_6	[39~78] Hz

The goal of this work is to qualitatively analyse how the start-up method influences the results that presents this new methodology based on the DWT of starting current. The DWT will be applied to current signals for different types of start-up in order to check if the method provides robustness for the detection of patterns associated with the failure. This is a key issue to ensure the generality of the method and to provide potential for their future implementation in diagnostic devices. Indeed, Sections 2 to 6 give an analysis of the different harmonics and perturbations that may be present in a healthy machine analysis since it is important to know their influence when performing the machine diagnosis via the DWT method.

2. Harmonics introduced by the induction motor itself

2.1. Rotor Slot Harmonics, Slot Permeance Harmonics

The magnetic flux density waves interact between the stator and rotor and vice versa thanks to the air permeability of the air gap. Some of these waves are produced by the interaction of the existing slots in the rotor and the stator. These waves induce in the current that flows through the stator windings two classes of harmonics whose frequencies are given by:

$$f_{RSH} = \left(1 \pm \lambda \frac{R}{p}(1-s)\right) f, \quad \lambda = 1, 2, 3 \ldots \tag{4}$$

where λ is an integer, R is the number of rotor slots, s the slip and f the fundamental frequency. There are two effects that can lead to the appearance of these components[15];

1- By rotor high-frequency currents induced from the stator by the rotating magnetic flux waves. Such currents generate in the stator electromotive forces at the same frequencies. These are the Rotor Slot Harmonics (RSH), top and bottom, and are the most relevant of those induced by a healthy rotor of an induction motor. For λ=1, the Principal Slot Harmonics (PSH, Upper (+) and Lower(-)) are obtained.

Their appearance in the spectrum depends on the number of pole pairs produced by the stator winding in the case of the Lower PSH and number of rotor bars in the case of Upper PSH and, in both cases, on combined to turn with the number of poles pairs of the flux density waves induced by the rotor and that generate the frequency components in the stator mentioned in (4)[15].

2- By self-inductance of the stator windings that induces in the own stator the components given in (4) due to changes in the permeability with the rotor angle. These are the Slot Permeance Harmonics and for its existence is not required as in the previous case that current flows through the rotor, being sufficient that the rotor is slotted so that by turning it, occur in the stator the effect referred in [15].

2.2. Saturation Harmonics

In saturated induction machines, changes in the values of the main flow density wave (and therefore in the saturation condition) are related to changes in the length of the air gap (and therefore of the permeability) when the rotor rotates. These changes induce current components in the stator whose frequencies are given by the following expression:

$$f_{SH} = \left(3 \pm \lambda \frac{R}{p}(1-s)\right) f, \quad \lambda = 1, 2, 3 \ldots \tag{5}$$

Those are the Saturation Harmonics (SHs, top (+) and bottom (-) and its appearance in the spectrum depends on the same combinations of poles pairs number in the stator and rotor bars that in the case of the PSHs as stated in[15].

Finally, there is a generic expression provided by some authors and that includes the components of the main harmonics introduced by the induction motor and the covers the expressions (4) and (5)[16]:

$$f_{H} = \left(\nu \pm \lambda \frac{R}{p}(1-s)\right) f, \quad \nu = 1, 3, 5 \ldots \tag{6}$$

Obtaining the components described in (4) for ν= 1 and those described in (5) for ν= 3.

3. Harmonics introduced by supply grid

In three-phase distribution grids, the time voltage harmonics contained in the supply voltage lead to time current harmonics in the stator current. The amplitudes of the most frequent harmonics typically decrease as their frequency increases; usual measurements are enough precise to obtain the amplitudes up to the harmonic with order 30, approximately. Within these, the most relevant voltage harmonics in an installation are the odd, whose ranks are 3th, 5th, 7th, 11th and 13th[12]. As a reference, Table 3 reflects the limit values of harmonic content for each specific harmonic, that should not be exceeded according to the IEC 61000-2-2 and that defines the compatibility levels of harmonic voltages in Low Voltage public grids:

Harmonic Range *n*	Harmonic Voltage %
3	5
5	6
7	5
11	3,5
13	3

Table 3. Distortion values related with main harmonics in three-phase supply networks

When the supply voltage is not symmetrical, on the one hand, the amplitudes of some RSHs or SHs (mainly the Upper PSH) may appear or increase; on the other hand, there is a significant increase in the amplitude of the third time harmonic (150 Hz); these facts do not occur when the voltage is symmetrical[13]. As practical examples of sections 2 and 3, Fig. 2 details the harmonic contents in the FFT spectrum of a healthy machine without load on steady state, with k= 1, R= 28, p= 2, f= 50 Hz and s= 0.006.

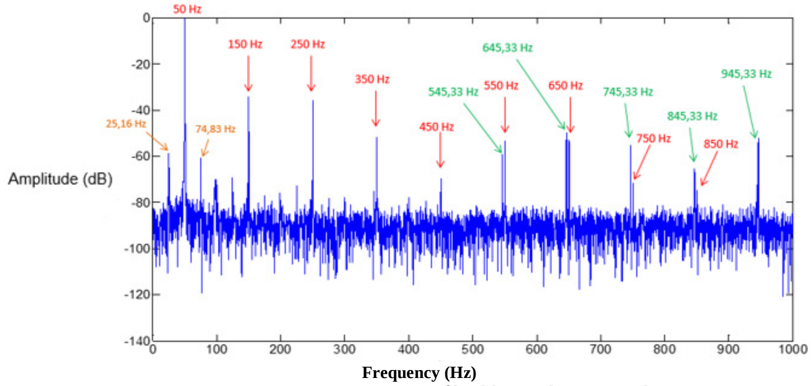

Fig.2. FFT Spectrum of healthy machine in steady state

In Fig. 2, the harmonics at 25,16 and 74,83 are due to the presence of a certain inherent eccentricity in the motor. The harmonic at 50 Hz corresponds to the Fundamental Frequency. The harmonics at 150 Hz, 250 Hz, 350 Hz, 450 Hz, 550 Hz, 650 Hz, 750 Hz and 850 Hz are current time harmonics. Within this group, note the higher amplitudes of the 3th, 5th, 7th, 11th and 13th harmonics, as commented in Section 3. On the other hand, the saturation harmonics (SH) are located at 545,33 Hz (Lower SH) and 845,33 (Upper SH),while the PSH are located at 645,33 Hz (Lower PSH) and 745,33Hz (Upper PSH). The harmonic at 945,33 Hz is obtained from(6) for v= 5(+).

Finally, in Fig. 3[13] is depicted the CWT analysis of the start-up of a healthy induction motor. This analysis enables to compare, on the one hand, the harmonics introduced by the grid with symmetrical (Left) and asymmetrical (Right) supply voltage. On the other side, the figure enables to observe how the PSHs and SHs evolve during the direct start-up, as the slip s changes between 1 and close to 0. When comparing the two graphs, it is observed the increments in the amplitudes of some SH and PSH, as well as of the third time harmonic when the supply is asymmetrical, which is in accordance with what stated in this section.

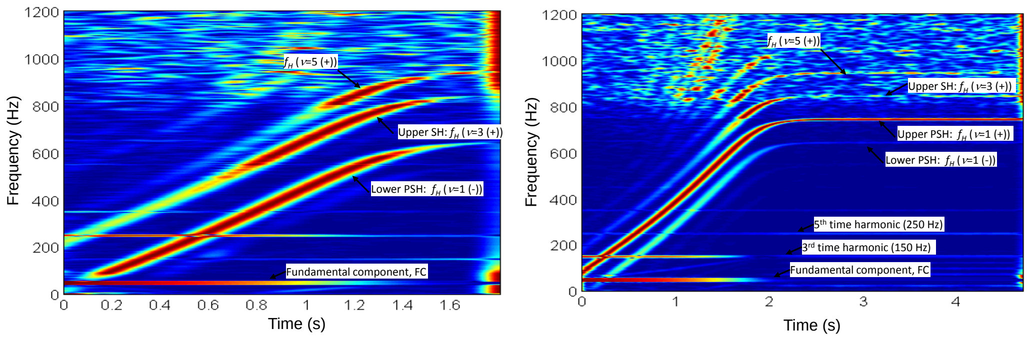

Fig.3. CWT analysis of a healthy machine statup current with: symmetrical supply voltage (left) and asymmetric supply voltage (right).

4. Other Effects; fluctuations of the load torque, couplings

In many industrial applications the induction motors are subject to torque fluctuations in the load that they are driving (e.g. mills, pumps, compressors). In other cases, the induction motors are fed with voltages with periodic fluctuations, situation that can arise in low power short circuit supply lines and that simultaneously feed other large machines time whose energy consumption is oscillating. Finally, it is also frequent to find coupling systems based on belts and pulleys or gear trains that are employed to vary speed relation. All of the previous elements (oscillating load torques, fluctuating supply voltages, coupling systems…) can lead to the increment of certain frequency components in the FFT spectrum of the steady-state stator current. All these components may eventually lead to a confuse diagnosis of the health of the machine when using the MCSA, as it has been demonstrated in previous works[1].

5. Harmonics produced by soft starters and frequency inverters

As proven in previous works[13, 18], the start-up of an induction motor using a soft starter usually leads to an increase in the intensity of the 5th and 7th time harmonics, as well as increases in the families with negative sign defined by (6). These facts can be observed when comparing the CWT time-frequency analysis of the startup current of a direct started motor with that of the motor started via soft starter[13, 18]. With regards to the motor start via frequency inverters, it is much more difficult to discern the evolutions of the harmonics present in the stator current signal, due to the fact that these devices also act on the fundamental frequency component[19]; hence, in this case, it is necessary the use of more optimized time-frequency tools to be able to extract the frequency evolutions of all the harmonics present in the current. With regards to fault diagnosis, it can be said that the start via inverter complicates the identification of the fault related harmonics present in the current signal and it makes necessary the use of more advanced and optimized time-frequency tools to detect their presence.

6. Disturbances produced in the start with electromechanical start-up systems

In many industrial applications, induction motors are started with other start modalities as: direct start-up, star-delta start-up, start via autotransformer, start with inserted resistors in the stator windings and start with inserted resistors in the rotor windings (for wound rotor induction motors). These start modalities and, more specifically, the commutation transients that take place in some of them, can lead to increments in some frequency components in the current spectrum. However, as it was proven in previous works, in general terms these frequency increments do not affect the observation of the eventual fault components present in the stator current signal, when transient based fault diagnosis methods are applied (either in the DWT-based methods or in the CWT-based methodologies).

7. Results and discussion

This section includes some experimental results that illustrate the considerations exposed in the previous section related to the harmonics introduced in the current spectrum by each specific phenomenon. We emphasize the repercussion on the start-up current harmonic content that is studied by using the DWT of the start-up current signal, that is a simple tool for its analysis and whose foundations were well exposed in previous works[1-3].

7.1. Signal analysis when harmonics resulting from fluctuations in the torque load as well as harmonics introduced by the coupling system are present.

The purpose of this experiment was to obtain a start-up signal equivalent to that of a motor coupled to a load that has a cyclical variable torque. The idea is to illustrate the problem that may appear in this situation since this phenomenon may lead to harmonics very similar to those introduced by an eventual rotor fault. To perform this test, the motor was coupled to a DC load and the excitation of the load was successively connected and disconnected at a commutation frequency of 3.3 Hz by using an automated system designed to this effect in the laboratory[3]. In this way, two components appear in the Fourier spectrum (Fig. 4 (Left)) at 46.6 Hz and 53.3 Hz, respectively[1]. These components are very similar to those that could be introduced due to an eventual fault, a fact that may lead to a wrong diagnostic. In this case, the DWT analysis of the start current may be very useful since no fault related pattern appears, hence discarding the presence of the failure (Fig. 4 (Right))[1].

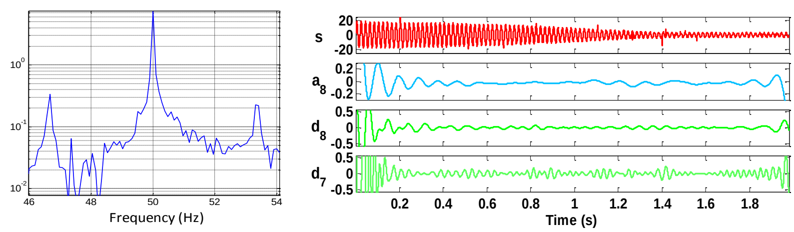

Fig.4. Healthy machine with fluctuating load torque: FFT analysis of current in steady state (left) and DWT analysis of start-up current (right)

With regards to the components that can be generated by the couplings system of the machine, Fig. 5 (Left) shows the FFT spectrum of a healthy machine in steady state. Note the presence of prominent frequency components that appear at both sides of the supply frequency; these are introduced by the coupling system between motor and load that in this case was based on belts and pulleys. These components may also lead to confusion in the diagnostic of eventual rotor damages. However, in the corresponding DWT analysis depicted in Fig. 5 (Right), as in the previous case, the appearance of the characteristic pattern that identifies the rotor asymmetry is not observed[1].

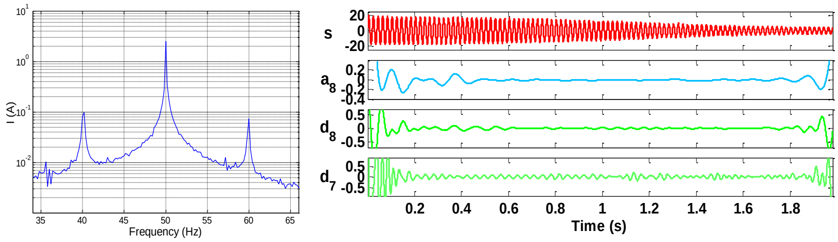

Fig.5. Loaded machine in healthy condition: FFT analysis of current in steady state (left) and DWT analysis of start-up current (right)

7.2. Signal analysis when harmonics produced by soft starters are present

Fig. 6 compares the direct and soft starter (ramp voltage and ramp voltage + limitation current) start-up for a healthy machine (graphs above) and for a machine with two broken bars (graphs below)[18]. The purpose of this experiment is to demonstrate that in spite of the harmonics introduced by the soft starter mentioned in Section 5, the DWT analysis can distinguish clearly between the bar breakage when present.

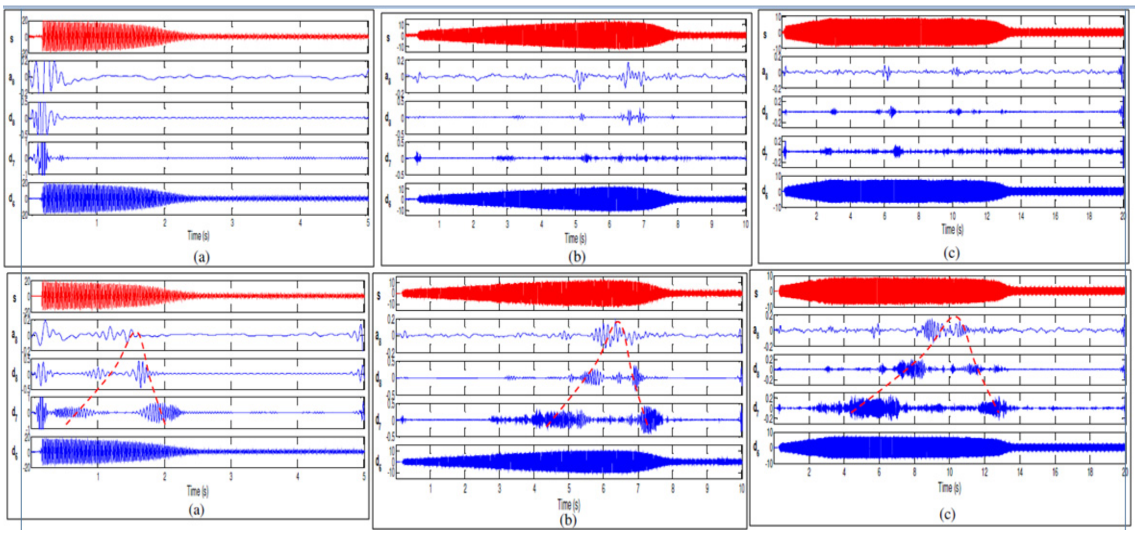

Fig. 6. DWT of the startup current for the healthy motor (above) and faulty motor (below) for: (a) line-started motor, (b) motor started with soft-starter (voltage ramp) and (c) motor started with soft-starter (voltage ramp+current limitation).

7.3. Analysis of signals when disturbances produced by electromechanical start-up systems are present

The following graphs (Fig. 7 (Left) and (Right)) depict the star-delta starts-up carried out with incorrect commutation for two laboratory motors: one of them (Left) without any malfunction and the other with provoked breakage of two rotor bars (Right). In spite of the appearance in the wavelet signals (a8, d8, d7) of the oscillations related to the incorrect switching at about the same time in each case, the "Λ" shaped pattern that identifies the bars breakage only appears in the signal (Right) associated with the motor with two broken bars, although in this case it would be necessary to fix appropriate scales to appreciate it.

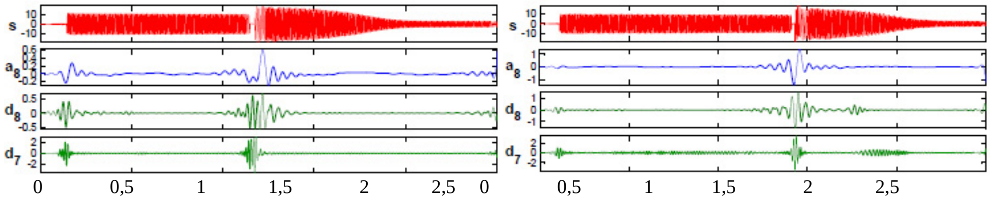

Fig.7. Star-delta start-up with incorrect commutation. (Left) healthy machine. (Right) machine with two broken bars

8. Conclusions

In the present work, a review has been made of the DWT analysis effectiveness for the detection of asymmetries in the rotor of an induction motor, analysing the influence of electronic and electromechanical starting systems more used in industry. In addition, the influence in the analysis of the most important harmonics that can appear in the operation of a healthy machine has been studied, such as those introduced by the supply network, the motor itself or those generated by the load that the motor is driving as well as those due to different types of load couplings. Within the cases studied, the experiments shown have been made taking into account the most adverse conditions for the detection of the fault characteristic pattern by the LSH evolution in the different frequency bands collected by the wavelet signals. With the exception of the start-up by using frequency inverters, for all other methods studied, the method has been shown to be reliable and robust, clearly differentiating between cases in which the machine is healthy and in which the rotor fault is present. The next task is to get the automated identification of the patterns associated with the fault, so that the method becomes a tool for maintenance in the industrial environment.

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