Very Accurate Time-Frequency Representation of Induction Motors Harmonics for Fault Diagnosis Under Arbitrary Load Variations.

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Abstract—**Induction motors work under steady state in many applications. Nevertheless, in some cases (e.g., wood cutting machine or pulp mixer in paper industries), the load continuously varies. In these cases, time-frequency transforms are needed to detect the evolutions of faulty harmonics, quantify their amplitudes and determine the severity of the fault. To achieve reliable results under challenging situations, a very precise time-frequency transform, which enables to very accurately plot the faulty harmonics evolutions, must be developed. The Dragon Transform is here proposed to address the problem. It can be seen, through simulation and experimental results, how the transform enables to plot up to five faulty harmonics under rotor asymmetry. Precision is so high that even the oscillations caused by ripple effect can be observed for the first time in the technical literature, enhancing the reliability of the diagnosis performed, and opening the path for a true solution of the problem.**

Index Terms—**Induction Motors, Load Oscillations, Signal analysis, Time-frequency transforms, Fault diagnosis.**

I. Introduction

Electrical machines play a key role in the manufacturing industry and its importance is quickly growing in the transport sector. The two types of electrical machines that dominate these sectors are the synchronous and induction machines. The industrial trend is to employ synchronous machines when the control of the speed and position in the industrial process is paramount. On the other hand, induction machines are preferred when the speed accuracy requirements are low. As in many industries the speed requirements are low, induction machines are generally the preferred option.

When induction motors are subjected to constant loads, they are directly fed from the grid if the final speed of the process is irrelevant, or from Variable Speed Drives (VSDs) if there is a need for a specific speed in the industrial process. In any case, during the normal operation load variations will occur, resulting in changes of the machine's speed, which can be severe in certain applications such as in a pulp mixer, in the paper industry, or in a trunk cutter, in the wood industry.

When induction motors operate under constant loads, their speed is constant, and the conventional Fast Fourier Transform (FFT) technique is used to diagnose them by obtaining the spectrum of their stator currents. As fault related frequencies are speed dependent, measuring or estimating their speed is compulsory [1] to correctly localize them in the frequency spectrum, quantify their amplitudes and determine whether there is a fault and its severity.

Load variations increase the stress induction machines are subjected to and consequently the chances of failure occurrence. Furthermore, the speed changes and with it the frequency of the fault components, preventing their diagnosis by using the FFT current spectrum. Hence, reliable diagnosis techniques when induction machines operate under variable loads must be developed to avoid undesirable shutdowns of the industrial processes.

The technical literature for the diagnosis of electrical machines under variable loads can be classified into three big groups. The first group includes techniques based in signal demodulation [2]–[10] which are less computationally demanding as they tend to focus on a specific harmonic or frequency bandwidth of the stator current spectrum. The second group contains time-frequency analysis techniques [11]–[18] which require a greater computational time than signal demodulation techniques but offer a global view of all the current harmonics in the current spectrum. The third group employs alternative techniques, [19] and [20], which do not fulfill in the two previous categories.

One of the first signal demodulation techniques for the diagnosis of induction machines under transient states is presented in [2] where rotor asymmetries in an induction motor fed from a Variable Speed Drive (VSD) are diagnosed. The diagnostic technique is carried out by acquiring the current and speed of the machine under an acceleration ramp of 5 Hz/s but the slip speed, which determines the actual fault frequency, is constant around 2 Hz. Then, the stator current is demodulated by a frequency shifting what allows the analysis of the current as if the machine was operating under short stationary regimes.

The frequency shifting idea presented in [2] is further developed in [3]–[5], where double fed induction motors are diagnosed, [6], where a squirrel cage induction machine is diagnosed, [7], where outer broken bars of a double cage

This work was supported by the Universitat Politècnica de València and the Spanish Ministry of Science, Innovation and Universities [FPU19/02698]

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squirrel cage induction motor is diagnosed and, [8], where a rotor asymmetry in a Wound Rotor Induction Machine (WRIM) is diagnosed. In [3]–[8] the Wavelet Transform (WT) and the Discrete Wavelet Transform (DWT) are employed for the extraction of the fault component from the stator current and the machines are subjected to acceleration or deceleration ramps which cause a fault frequency change of 4.44 Hz/s [3]–[7] and 0.93 Hz/s in [8]. The difference between these publications is how the energy of the frequency band extracted by the WT is computed to determine the existence or not of a fault. However, all these techniques share the same drawback. They assume that the increase of the energy in the extracted frequency band is only due to the existence of a fault component. Therefore, if there is a change in the load conditions of the induction machine the energy of the extracted frequency band can increase causing false positives.

To overcome the false positive problem an improvement to the techniques presented in [3]–[8] is developed in [9], where the eccentricity fault is diagnosed, and [10], where the rotor and stator asymmetries are diagnosed, by calculating the Instantaneous Frequency (IF) of the extracted frequency band. In [9] and [10] the machines diagnosed are subjected to random increasing and decreasing speed ramps which cause a fault frequency change of 0.42 Hz/s and 1.66 Hz/s respectively. The computation of the IF of the extracted frequency band combined with the measurement of the speed in [9] and [10] allows to discern whether the energy in it is due to a fault or due to other external factors, such as oscillating loads, overcoming the main drawback, false positives, of [3]–[8] at the expense of requiring a speed measurement.

One of the first publications using time-frequency analysis techniques for the diagnosis of broken bars and bearing faults in induction machines is presented in [11]. The fault diagnosis is carried out by the computation of the Short Time Fourier Transform (STFT) and Gabor Transform (GT), which is a particular case of the STFT. In [12] the diagnosis of the eccentricity fault in induction machines is performed through the Wigner Ville Distribution (WVD) and in [13] the use of the DWT combined with the STFT is employed for the diagnosis of broken bars and stator short-circuits. Although it is stated the potential of the time-frequency techniques for the diagnosis of induction machines under variable loads, the different loads analyzed in [11]–[13] can be considered a succession of steady states as the variation of the load conditions is very slow.

In [14] the WVD is employed to diagnose rotor asymmetries in a WRIM under random increasing and decreasing speed ramps which cause a fault frequency change of 1.66 Hz/s. This technique is enhanced for the diagnosis of broken bars in squirrel cage induction machines by adding particle filter to extract the fault component [15] where the machines are subjected to random speed changes with a maximum fault frequency change of 4 Hz/s. However, the WVD is suitable for the analysis of single component frequency signals, as artifacts, not real frequency components, appear in the frequency spectrum when multi frequency signals are analyzed with the WVD. To overcome the problem of the WDV artifacts, in [16] is presented an atom time frequency technique based on the adaptative slope transform to diagnose rotor and stator faults of a WRIM under load oscillations that cause a fault frequency change of 1.66 Hz/s. However, both techniques share the drawback of needing an accurate enough speed reading to perform a reliable diagnosis.

The last time-frequency technique developed for the diagnosis of induction machines operating in variable load conditions is the Harmonic Order Tracking Analysis (HOTA), [17] and [18], which is based on the computation of the Gabor transform as in [11]. In [17] an asymmetry in a WRIM under transient conditions, which cause a change in the fault frequency up to 0.26 Hz/s, is diagnosed, whereas in [18] an induction machine fed from a VSD with constant and transient loads is diagnosed for broken bars. However, in [18] the rate of change of the load is not shown. In any case, time frequency analysis techniques based in the STFT, as it is the GT, are not adequate for great frequency changes in the fault frequency.

Finally, other techniques employed for the diagnosis of electrical machines are the ones presented in [19] and [20]. In [19] the broken bars of induction motors are diagnosed under a slow change in the torque load by computing the instant active and reactive powers of the induction machine. In [20] a rotor asymmetry in a wound rotor induction generator fed from a VSD is diagnosed by measuring the DC component of the space vector control when the machine is subjected to a deceleration ramp which cause a change in the fault frequency of 4.44 Hz/s. The major drawback of this alternative techniques is that they do not allow the discrimination of the fault.

This paper proposes a new time frequency analysis tool for the diagnostic of induction machines under variable loads based on the Dragon Transform. The tool is successfully tested by diagnosis simulations and real tests with machines enduring constant transients. The tool allows to discern false positives due to load oscillations and follows the harmonic in a more accurate way. This paper is organized as follows: Section II shows the theory of the Dragon Transform and its suitability for load oscillations. Section III presents the diagnosis results for simulated signals and section IV shows the experimental results. Finally, section V shows the conclusions of this work.

II. Dragon Transform for load oscillations

As stated in the introduction, time-frequency transforms can be classified in two types: transforms which try to determine the main frequency in a certain frequency band, and transforms which try to plot all the evolutions present in the entire time-frequency plane. In order to obtain the highest amount of information, and better represent the frequency content of the signal and its time evolution, continuous time-frequency transforms are the best option.

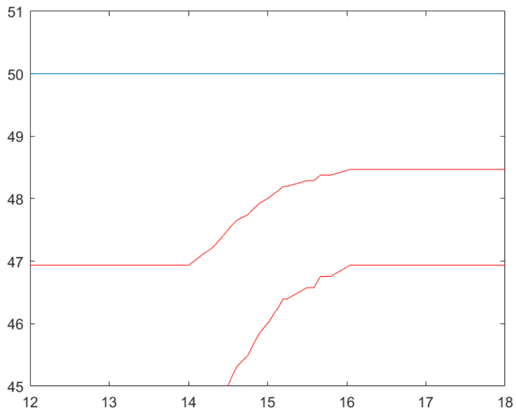

Fig. 1. Theoretical evolutions of the harmonics to be captured.

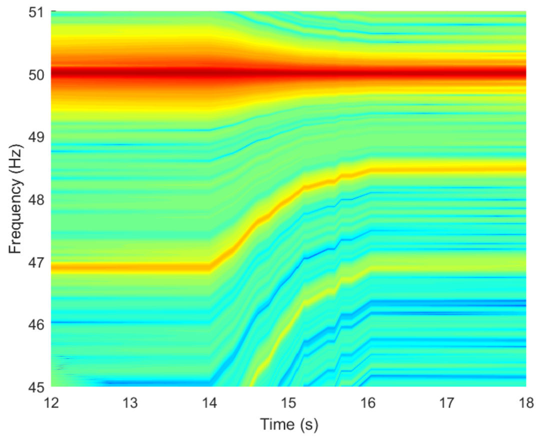

Fig. 2. Dragon Transform result.

Inside this set, transforms are mainly divided in two types: Wigner-Ville distributions (WVD), and atom-based time-frequency transforms. The main problem of the WVD is that cross terms appear when a signal with multiple components is analysed. Smoothed versions of this transform have been proposed trying to solve this problem. On the other hand, atom-based time-frequency transforms do not produce cross-terms, but the energy of the harmonics appear scattered around their real evolution. In other words, the evolutions, which physically are perfectly thin lines (since for each time instant, a component has only one frequency), they appear represented as lines with a certain thickness.

Dragon Transform was originally proposed to enable the diagnosis of bar breakages in induction motors started-up with frequency converters [21]. This is a very difficult problem, since the harmonics describe evolutions which are very close in the t-f plane: a transform able to represent these evolutions as very thin lines is necessary, so they are not mixed up. The Dragon Transform does not eliminate the energy scattering, it forces the scattering to take place throughout the component evolution. As a result, the evolutions appear as very thin lines, and the problem is solved.

For instance, Fig. 1 represents the theoretical evolutions of the harmonics to be captured in an induction motor stator current: the fundamental component traces a horizontal line, while the Lower Sideband Harmonic (LSH) evolves below under a load oscillation (from higher to lower load, since its frequency increases). Below the LSH, a part of the evolution of a secondary asymmetry harmonic can be also observed.

The Dragon Transform result, shown in Fig. 2, shows these evolutions as perfectly thin lines. This is achieved by forcing the dispersion of the energy along the evolution of the current component itself, instead of around it. This is the base proposed in the present paper, to achieve the diagnosis of an induction motor under arbitrary load oscillations, when the harmonics evolutions can describe very complex paths. In the following sections, the capabilities of the transform are tested, using simulation and experimental results.

TABLE I
LOAD DESCRIPTION

	Type	Frequency	% of Rated load
L1	Constant	-	100
L2	Sinusoidal	0.3 Hz	75 to 95
L3	Sinusoidal	1.5 Hz	75 to 95
L4	Sinusoidal	0.3 Hz	30 to 90
L5	Non-periodic	Slow oscillations	30 to 90
L6	Non-periodic	Fast oscillations	30 to 90

III. Simulation Results

In this section, the Dragon Transform is input with simulated signals from a dynamic model of a 4-pole, 4 kW induction motor (more data in Appendix). The model is implemented in MATLAB and solved using a 4th order Runge-kutta with a step size of 10^{-4} s and the following assumptions: infinite permeability, no saturation, constant air-gap and arbitrary number of spatial harmonics considered in inductance and torque calculations. Table I shows the load characteristics of the six cases under analysis (the rest of the model parameters remain unchanged). For each of these six cases, which include constant (L1); periodic (L2, L3, L4) and non-periodic (L5, L6) loads, three states are considered: healthy, one broken bar and two broken bars. The resulting simulated currents are then decimated from 10 kHz to 250 Hz and input to the Dragon Transform along with the simulated slip.

A. Results

The Dragon Transform results are presented in Fig. 3 to Fig. 8, where the time-frequency spectrum has been normalized in dB with respect to the fundamental component. In each of these figures, the three states are represented: healthy (a), one broken bar (b) and two broken bars (c). The frequency range of analysis has been chosen in such a way that the LSH (Lower Sideband Harmonic) $(f_{LSH} = [1 - 2s]f_0)$ is always the lowest harmonic seen in the spectrum. The other two harmonics that are expected to be seen are: the

TABLE II
MEAN VALUE OF LSH AMPLITUDE (IN DB WITH RESPECT TO THE FUNDAMENTAL COMPONENT) FOR EACH CASE ANALYZED.

	L1	L2	L3	L4	L5	L6
Healthy	-45.82	-44.35	-45.06	-38.23	-37.77	-36.63
1 broken bar	-30.09	-31.38	-31.42	-30.05	-30.09	-31.16
2 broken bars	-24.99	-24.31	-24.34	-25.58	-26.34	-27.85

fundamental component at constant f_0 Hz (all cases) and the load oscillation harmonic at constant $f_0 - f_{osc}$ Hz (periodic load cases). Finally, it must be noted that due to the speed oscillations caused by the breakages of the bars, the slip is slightly different between the three states and therefore so is the LSH frequency evolution.

1) Constant load: Figure 3 shows the results for the case of constant load. As the fault severity is increased, a pattern is revealed at around 46.7 Hz. This pattern perfectly matches the LSH evolution according to its theoretical formula when the simulated slip is used. Moreover, when comparing Fig. 3b (one broken bar) with Fig. 3c (two broken bars), it can also be observed how the pattern gets darker (which means more energy), clearly indicating an increase in the severity of the fault. Finally, it must be noted that, although load is constant, the torque ripple caused by the bar breakage creates a periodic oscillation in the motor speed, and therefore, in the LSH frequency. Thanks to the Dragon Transform, this is the first time in which the LSH evolution is plotted with a precision such that even the speed ripple effect can be observed.

2) Periodic load: Figure 4, 5 and 6 show the results for the cases of periodic load oscillations. In all of them, the appearance of the pattern can be perceived, as well as the difference between the three states. Furthermore, in Fig. 5, the load oscillation harmonic can also be clearly perceived at a constant 48.5 Hz. In the other two cases, this harmonic appears at 49.7 Hz, therefore, although it is still possible to guess its position, a closer zoom would be needed.

3) Non-periodic load: Figure 7 and 8 show the results for the cases of non-periodic load oscillations. In these two cases, it is worth to highlight that despite the abrupt changes in the load, the Dragon Transform manages to perfectly follow the evolution of the LSH in a very fine and precise way (thin frequency line with very low leakage). This not only makes it possible to clearly show the difference between the different states, but also allows a much more precise quantification of the harmonic and therefore a much more accurate diagnosis.

4) Amplitude quantification: Table II shows the mean value of the LSH amplitude (in dB with respect to the fundamental component) for each case and state analyzed. This value is obtained by computing the average of the maximum amplitudes found in a frequency band (0.2 Hz) centered at the exact position of the LSH at each time instant. For all cases, as fault severity increases, amplitude increases, showing its great usefulness as a diagnostic tool.

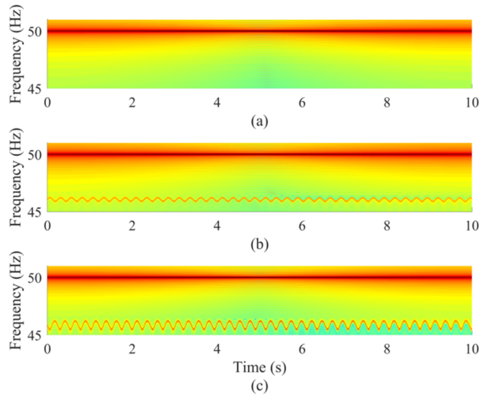

Fig. 3. Simulation results at constant load (L1): healthy (a), 1 broken bar (b) and 2 broken bars (c).

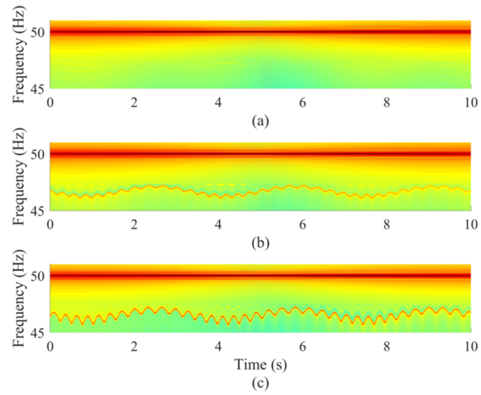

Fig. 4. Simulation results with periodic load (L2): healthy (a), 1 broken bar (b) and 2 broken bars (c).

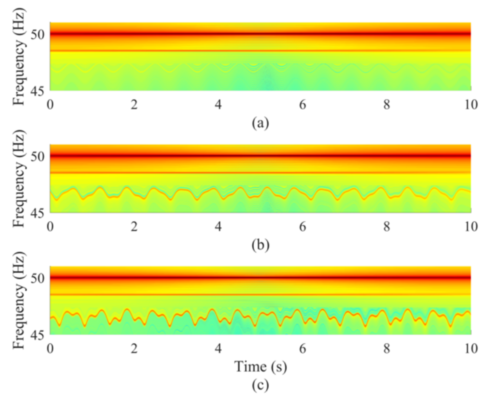

Fig. 5. Simulation results with periodic load (L3): healthy (a), 1 broken bar (b) and 2 broken bars (c).

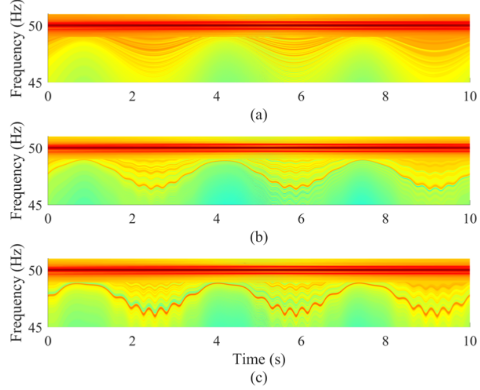

Fig. 6. Simulation results with periodic load (L4): healthy (a), 1 broken bar (b) and 2 broken bars (c).

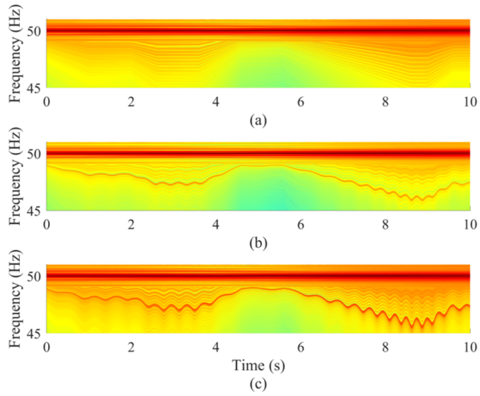

Fig. 7. Simulation results with non-periodic load (L5): healthy (a), 1 broken bar (b) and 2 broken bars (c).

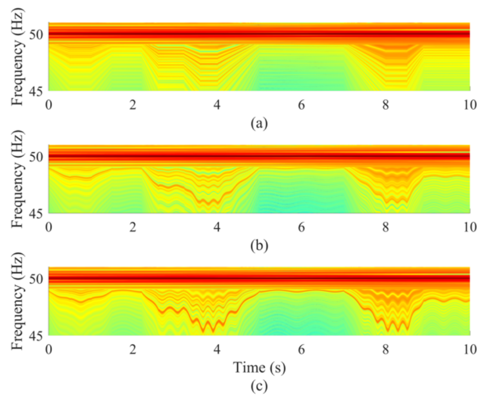

Fig. 8. Simulation results with non-periodic load (L6): healthy (a), 1 broken bar (b) and 2 broken bars (c).

IV. Experimental results

To validate the methodology, a BKB universal machine is tested (see appendix for its characteristics). A DC machine moves the rotor over the synchronous speed to achieve generator mode. The DC machine is controlled to perform during each test the same speed fluctuations. Nevertheless, when the asymmetry appears, speed ripple takes place. Rotor and stator windings are primary and secondary windings respectively. The primary winding is connected to a three-phase supply source of 160V, and its current is measured to perform diagnosis. The secondary winding is short-circuited, while additional resistances are connected in series to a phase, simulating different degrees of asymmetries. In this paper, the healthy case is compared with a 4.15 Ω additional resistance. This test is equivalent to a wounded rotor induction generator with a rotor fault.

The theoretical evolutions of the harmonics are shown in Fig. 9: fundamental component evolution is plotted, together with the rotor asymmetry harmonics with frequencies $f = (1 \pm 2ks)\, f_0$, being s the slip, f_0 the main supply frequency and k a positive integer, which in this case is equal to 1, 2 and 3 (the last number, only for the negative sign). Faulty case plotted in Fig. 9b shows a ripple effect caused by the asymmetry in the secondary winding.

Figure 10 shows the Dragon Transform results when analysing the primary winding currents: healthy (Fig. 10a) and faulty (Fig. 10b). In both cases, the fundamental component appears as a very clear horizontal line. Due to the precision of the transform used, the LSH appears even in the healthy case result. Its trajectory is at higher frequencies than the fundamental component, since the machine is operating as a generator. In the faulty case, its amplitude highly increases (from -45 to -17 dB). Moreover, up to five faulty harmonics are detected in faulty state. Finally, this is the first result in which the trajectories are plotted in such a precision that even the oscillations caused by ripple effect can be observed. All this enhances the reliability of the diagnosis performed.

V. Conclusions

The use of the Dragon Transform has been proposed for the diagnosis of induction motors under arbitrary load oscillations. Thanks to the transform capabilities, the evolutions of the faulty harmonics can be observed in the t-f plot as very thin lines. First, the transform has been tested using simulations with periodic loads, slowly and rapidly varying, and following different patterns. Second, it has been proven how the transform enables to follow the LSH evolution also under arbitrary non-periodic loads. Detection of rotor asymmetry has been tested too with experimental results, showing how the transform enables to follow the evolution of the faulty harmonics, even under healthy state (caused by the inherent asymmetry). For the first time in the technical literature, it can be seen how, when the fault appears, speed ripple effect takes place, and high frequency oscillations are superimposed with the original trajectory of the harmonics.

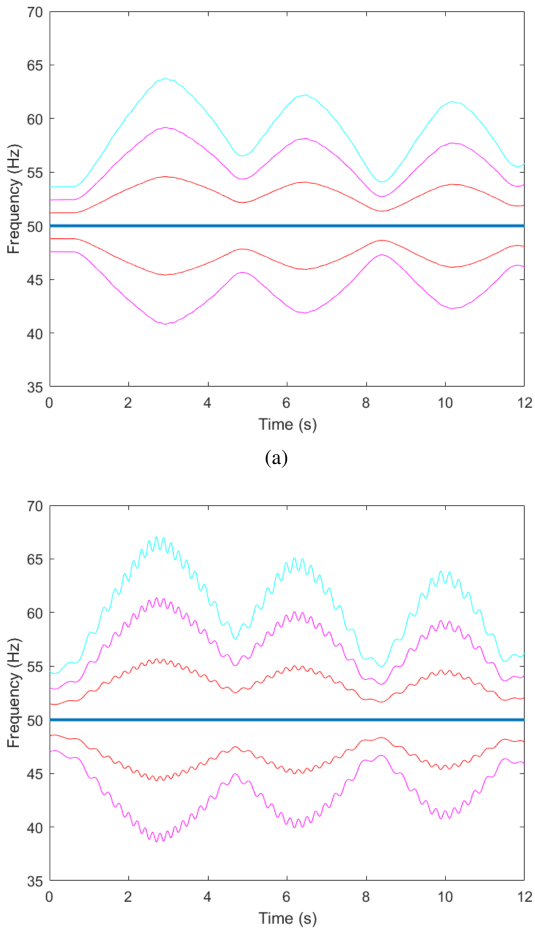

Fig. 9. Theoretical evolutions for the BKB universal machine working as induction generator: healthy (a) and asymmetry in the secondary winding (b).

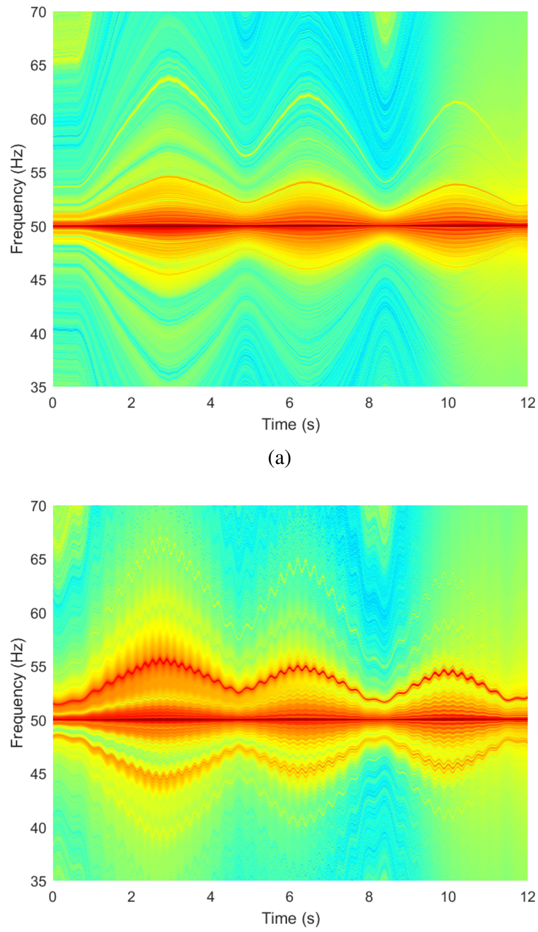

Fig. 10. Dragon transform results of the BKB universal machine working as induction generator: healthy (a) and asymmetry in the secondary winding (b).

Up to five faulty harmonics evolutions are depicted with high precision, which enables a very reliable diagnosis.

VI. Appendix

BKB characteristics:

- 1.5 kW, 50 Hz, 1 pair of poles, 3200 rpm (working as a generator).
- Stator Winding: 240 V, rated current 5.5A star-connected, stator resistance 4.4 ohm/phase.
- Rotor Winding: rated current 8A, delta-connected, rotor resistance 10.15 ohm/phase.

Simulated motor characteristics: $U_N = 400V$, Connection = Y, $N_{bars} = 28$, $p = 2$, $T_N = 26.6$, $J = 0.03\ kg/m^2$.

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VII. BIOGRAPHIES

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