Wire Rope Fault Detection in a Hoisting Winch System by Motor Torque and Current Signature Analysis

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Abstract—The aim of this paper is to analyze theoretically and experimentally the stator current and load torque of a three-phase induction machine in a hoisting winch system. This is performed in order to show how these variables are influenced by the wire rope faulty conditions. When the wire rope is subject to axial and torsional loads, the outer strands can be separated from the core in a permanent way and make the rope less reliable. The term "birdcaging" is used to describe this type of phenomenon by giving a permanent appearance of a wire rope forced into compression. In a hoisting winch system, the rope is bent over a drum and a pulley, and it is torsionally stressed by the fleet angle between them. In this paper, the effect of the fleet angle is observed in the stator current and the load torque in order to detect the "birdcaging" effect. This study is performed on a 22-kW three-phase squirrel-cage induction machine driving a reduced scale winch system, and it presents an original noninvasive way to detect a wire rope fault condition.

Index Terms-Diagnosis, fault detection, hoisting winch system, induction machine, load torque, mechanical fault, mechanical load, online condition monitoring, stator current, wire rope "birdcaging".

NOMENCLATURE

$T_{\rm wd}(t)$	Load torque driven by the winch drum.
T_0	Average load torque.
$T_{\rm bc}, f_{\rm bc}, \phi_{\rm bc}$	Magnitude, frequency, and phase angle of the
	torsional vibration induced by the "birdcaging"
	effect.
$u(t_{\rm lim})$	Rectangular time-dependent window associ-
	ated to the duration of the "birdcaging" effect.
$t_{\rm in}, t_{\rm fin}$	Initial and final times which define the rectan-
	gular window.
α	Fleet angle between the rope and the plane
	normal to the axis of the pulley.
I(t)	Stator current.
I_s	Magnitude of the stator current component re-
	sulting from a healthy stator side.

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Magnitude of the stator current component pro duced by the rotor-induced electromotive forc		
Modulation index due to the "birdcaging'		
effect.		
Power supply frequency.		
Rotor speed frequency.		

- Frequency characteristic of the "birdcaging" $f_{\rm bc}$ effect.
- Sampling frequency of the data acquisition F_s system.

I. INTRODUCTION

R ECENTLY, condition monitoring of electrical machines in complex industrial systems has received deep attention because it allows increasing the global reliability and decreasing the loss of production due to the different possible faults. Therefore, many research works have been performed in the field of condition monitoring for both electrical and mechanical parts with noninvasive sensors. In this way, advanced methods have been proposed from the sensor position and implementation to the final decision process passing through modern signal processing techniques. Usually, two classes of faults in electrical machines are considered, and they are related to electrical and mechanical parts [1]. In the case of induction machines, the most important electrical faults are related to the rotor side, being the result of broken rotor bars or cracked endrings. For the stator side, the most frequent faults are based on opening or shorting of turns of phase windings. On the other hand, the mechanical faults can be classified as bearing defects [2]–[7], eccentricities [8]–[10], and gearbox failures [11], [12]. From a mechanical engineering point of view, the different possible faults are mainly related to tooth breakage, tooth root crack, surface wear, or surface spalling.

Nowadays, the motor current, as well as the torque, the power, and the flux signature analyses have been considered as interesting methods for both mechanical and electrical fault detections. All these techniques avoid invasive sensors, and they can be implemented in almost all the industrial applications using electrical machines. In all these cases, the electrical machine being the prime mover or an auxiliary component can be considered as a sensor itself for the global system.

The most important method is based on the monitoring of the stator current in the so-called motor current signature analysis

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(MCSA) to evaluate the electrical and the mechanical faults by verifying magnitudes of different frequencies in the line current spectrum [13]–[16]. For example, the evaluation of the magnitudes of the sideband frequencies around the fundamental of the stator current is an indicator of the rotor squirrel-cage health.

Several techniques have been proposed to show the effect of torque oscillations on the stator current for monitoring purposes [13]-[15]. In [13], the authors have demonstrated even by experiments that load torque oscillations make the stator current modulated in phase. Therefore, this is a proof that MCSA is convenient for mechanical monitoring purposes. As the rotational frequency components can be considered as factors of torque oscillations from the load point of view, it can be concluded that they will influence both the electromagnetic torque and the stator current. In [14], the detection of small torque oscillations in induction machine drives during speed transients by the stator current analysis has been studied. In this work, it is mentioned that these oscillations can be the consequence of mechanical faults. In [16], the stator current and the load torque of a three-phase induction machine in a hoisting winch system have been analyzed even by experiments. This has been done to show how they are influenced by the wire rope faulty condition (deformation). By using noninvasive sensors for monitoring mechanical faults, the diagnostic techniques are interesting since they can be both cheap and reliable. However, there are not yet many contributions using this approach at the system level. An example of a simple mechanical component is the wire rope in a hoisting winch system which has been analyzed herewith.

Wire ropes are used particularly in such systems where high load capacity combined with flexibility of the load carrying elements and the inherent damage tolerance are required. Inspection of a wire rope is necessary to decide whether it is necessary to replace it [17]. The detectable condition that determines the appropriate moment to discard a wire rope should reflect the mode of operation, the mechanism of degradation relevant to the application, the consequences of the failure, the frequency, and the reliability of the inspection [18]. Early replacement of a wire rope can also be caused by structure deformation which may be the result of an excessive wear or an unusual load pattern [19]. The magnetic flux leakage method is currently the most reliable and cost-effective inspection technique for nondestructive testing of a wire rope [20], [21]. This technique allows measuring the fringe fields near the rope surface to detect local defects such as broken wires, corrosion pitting, or local wear. For this purpose, Hall effect sensors, induction coils, and other types of magnetic sensors are used [22], [23]. It measures also changes in the magnetic flux passing through a short length of the rope to quantify changes in the global wire cross section [24], [25].

The acoustic emission method of inspection has been developed for continuous rope monitoring with transient elastic stress waves generated by the quick release of energy within the material. Within a wire rope, the main sources of detectable acoustic emission include wire break, interwire fretting, and corrosion. The most realistic application of acoustic emission technology to wire rope monitoring is the detection and the location of wire breakages [25]–[27]. Both electromagnetic and acoustic emission techniques need invasive sensors for efficient fault detection performances.

Wire ropes which are subject to twist counter in the direction of the strand winding are loaded in compression, and they can suffer from the "birdcaging" effect when the strands open up to leave the central void surrounded by a complex of strands [28]. This phenomenon represents a torsional instability inducing a structural deformation which involves damage of the wire rope defined by a local buckling. The rope buckling is a result of a torsional instability leading to a severe permanent deformation [29]. These wire rope deteriorations are the results of fatigue, corrosion, abrasion, and mechanical damage. They have to be detected in a mandatory way to avoid catastrophic consequences for the complete system.

This paper analyzes the "birdcaging" effect of a running wire rope passing over a pulley, with the load torque at the winch drum and by measuring the stator current of the induction machine which drives the hoisting winch system. For this purpose, a prototype of a hoisting winch system driven by a 22-kW 230-V/400-V 47-Hz two-pole-pair three-phase squirrel-cage induction machine has been designed. This has been done in order to show the influence of the faulty wire rope on both the stator current and the load torque. This study presents an original noninvasive way to detect wire rope fault conditions by using the induction machine stator current.

II. WIRE ROPE "BIRDCAGING" IN HOISTING WINCH SYSTEMS

A. Definition of the "Birdcaging" Effect

Steel wire ropes are critical load-bearing components in a wide range of applications such as cranes, lifts, or mine haulages [30]. A steel wire rope is a very complex component which consists of many strands of helical form twisted together to make a completed structure combining axial strength and stiffness with flexibility in bending [30], [31]. Each strand consists of a number of wires laid in helical form around a strand core which may be a single wire or a group of wires. Structurally, the wire rope is twisted tightly between strands and strands and between wires and wires. Therefore, a small relative sliding among strands and wires occurs when the rope is subject to the axial tension load and the bending stretch load on the drum and on the guide wheel, which leads to the fretting between steel wires. The fretting of steel wires causes damages and crack initialization and propagation, as well as fracture failure of the wires [32].

Sometimes, rope distortion, such as the loss of strands, the "birdcaging" effect, or mechanical damage, can be found in many applications. These faults contributed to the rope deterioration in service due to fatigue, corrosion, abrasion, and any other mechanical stress. In sensible applications, the rope health has to be monitored continuously to ensure its safe mechanical properties. In the case of huge deterioration, it is important to discard it in favor of a maximum allowable service life [25], [33]–[39].

The manufacturing process of a typical wire rope results in the combination of axial strength and stiffness with bending



Fig. 1. Some cases of "birdcaging" effect in wire ropes [42]. [(a) and (b)] Deformed rotation-resistant wire rope. (c) Unlaid wire rope. (d) Surplus of strand lengths in the steel core.

flexibility. A further consequence of the geometry of classical steel ropes is that they are torsionally active, generating a torque in response to the tensile load when ends are constrained against rotation or conversely twisted around their axis when one end is not constrained. Then, this last condition generates large torsion fatigue. Torsional oscillations are the consequences of tensile load fluctuations [37], [40]–[42], as well as torsional oscillations leading to fluctuations in the rope tensile load. When a rope is twisted, the original construction is modified. This deformation increases the length of outer wires compared to the core wires and makes the rope less efficient. The term "birdcaging" effect is used to describe this type of phenomenon, giving a permanent appearance of a wire rope forced into compression [43]–[45] (Fig. 1).

B. Mechanical Effect on the Pulley

The ideal operating condition of a wire rope in hoisting winch systems is the perfect alignment of the rope in the vertical axis of the pulley by entering and leaving the pulley groove [Fig. 2(a)]. Nevertheless, this condition cannot be practically verified because the fleet angle is introduced by both the relative position between the drum and the pulley and their relative dimensions [Fig. 2(b)]. The fleet angle is the angle between the rope and the plane normal to the axis of the drum or the pulley. If the fleet angle is too large, the rope tends to abrade on the adjacent wrap or the groove flank [18]. The maximum angle of deviation of the rope from the axis of the pulley groove must not exceed 1.5° [44]. Excessive fleet angles can cause serious damages to the wire rope, the pulley, and the drum. Severe friction results when the rope wears against groove walls, grinding them down and causing the rope to become bruised or crushed. The fleet angle must be minimized for the best wire rope service. In practice, a slight fleet angle between the rope and the plane of the pulley cannot always be avoided.

With a large fleet angle, the rope does not enter in the pulley at the lowest point of the groove. It touches initially the groove on the flange and then rolls into the bottom of the groove. This rolling action (Fig. 3) twists the rope around itself, with the direction perpendicular to the pulley rotation [44], [45]. The



Fig. 2. Operating condition of the wire rope on the pulley: (a) Ideal direction and (b) real direction.



Fig. 3. Wire rope rolling to the bottom of the pulley groove because of a large fleet angle.

more the friction effect at the point of contact is, the more significant the twist effect is.

C. Influence on the Drum Torque

When the wire rope structure is deformed because of the "birdcaging" effect, the friction produced by the fleet angle is increased. In this condition, the wire rope rotation around its axis is important, and it is increasing the torque friction up to the slip condition where the rotation is reversed. This effect is producing an oscillatory torsion on the running wire rope for the segment modified by the "birdcaging" effect. This torsional oscillation leads to fluctuations in the rope tensile load and then in the load torque driven by the winch drum. When the wire rope "birdcaging" segment is passing on the pulley, this load torque can be expressed as [11], [13], [14]

$$T_{\rm wd}(t) = T_0 + u(t_{\rm lim}) \cdot T_{\rm bc} \cos(2\pi f_{\rm bc} t - \phi_{\rm bc}) \qquad (1)$$

where T_0 is the average load torque, $T_{\rm bc}$, $f_{\rm bc}$, and $\phi_{\rm bc}$ are the magnitude, the frequency, and the phase angle, respectively, of the torsional vibration induced in the tensile load by the wire rope segment affected by the "birdcaging" effect, and $u(t_{\rm lim})$ is a rectangular time-dependent window which is defined as

$$u(t_{\rm lim}) \stackrel{\Delta}{=} \begin{cases} 1, & \text{for } t_{\rm in} \le t \le t_{\rm fin} \\ 0, & \text{otherwise} \end{cases}$$
(2)

with $t_{\rm in}$ being the initial time when the wire rope "birdcaging" segment reaches the pulley and $t_{\rm fin}$ being the final time when the effect of this perturbation is fully attenuated in the load torque. Theoretically, the frequency component induced by the "birdcaging" effect on the winch drum load torque can be localized in the spectrogram as

$$f_{\rm wd-bc}(t) = u(t_{\rm lim}) \cdot f_{\rm bc}.$$
(3)

Every torsional vibration in the mechanical system has an influence on the load torque applied at the induction machine rotor side. Then, the wire rope "birdcaging" effect on the stator current can be observed as a phase modulation and can be formulated as follows [11], [13], [14]:

$$I(t) = I_s \sin(2\pi f_s t) + I_r \sin[2\pi f_s t + u(t_{\rm lim}) \cdot \beta \cos(2\pi f_{\rm bc} t)]$$

$$\tag{4}$$

where f_s is the power supply frequency and β is the modulation index introduced by the wire rope "birdcaging" perturbation. The first term $I_s \sin(2\pi f_s t)$ represents the stator current resulting from a healthy stator side, and the second one is the current component produced by the rotor-induced *EMF* on the stator side. When the wire rope "birdcaging" segment is passing on the pulley, $u(t_{\text{lim}}) = 1$, and then, the load torque perturbation modulates in phase the stator current in a transient time. Otherwise, $u(t_{\text{lim}}) = 0$, and no modulation effect is present in the stator current. Theoretically, the frequency component induced by the "birdcaging" effect on the stator current can be localized in the spectrogram as

$$f_{s-bc}(t) = f_s \pm u(t_{\lim}) \cdot m \cdot f_{bc}$$
⁽⁵⁾

with m = 1, 2, 3, ...

III. EXPERIMENTAL RESULTS

A. Test-Bed Description

A special test bed has been designed in order to show the influence of the wire rope "birdcaging" effect on the winch drum load torque and on the stator current of the induction machine which drives the hoisting winch system. This test bed consists of two winches of the same characteristics. Winch A is used for hoisting purposes, and winch B is used to simulate the load operating conditions of winch A (Fig. 4). The electrical machine driving each winch is a 22-kW 47-Hz 230-V/



Fig. 4. Test-bed configuration.



Fig. 5. Practical simulation of the "birdcaging" effect on a wire rope: (a) Copper wire of diameter 1 mm wound on a length of 100 mm and (b) copper wire of diameter 2.6 mm wound on a length of 85 mm.

400-V two-pole-pair three-phase squirrel-cage induction machine which is connected to a three-stage planetary gearbox with a reduction ratio of 1:77. Winch A is driven by a closedloop speed control to ensure a constant speed in both winding and unwinding processes of the wire rope for any load between a minimum and a maximum. Winch B is driven by a closedloop torque control to simulate a constant load on the wire rope at any speed in both winding and unwinding situations. Between the two winches, the wire rope is installed passing by a sliding pulley, which minimizes the fleet angle. The wire rope has a diameter of 14 mm, and the "birdcaging" effect is simulated by winding around the rope a thin wire in a nearuniform way in order to replicate an increase of the diameter on a given wire rope segment (Fig. 1). In this way, two wires of diameters 1.0 and 2.6 mm wound on lengths of 100 and 85 mm, respectively, have been used to simulate two levels of modified diameter (Fig. 5). For the first case, no visible presence of 14% of wire rope diameter change has been detected in the different signals, and this case has been no longer investigated. However,



Fig. 6. Load torque at the drum at the instant when the segment of the modified wire rope is passing on the pulley (300 daN of load level). (a) Signal in the time domain. (b) Time–frequency representation in the frequency bandwidth [0 Hz, 8 Hz].

in the second case with 37% of wire rope diameter change, it has been easily detected in all the observed signals as it will be presented herewith.

The stator current of the induction machine driving winch A and the load torque at the drum are measured using a 24-b data acquisition system associated to a personal computer. The proposed setup has been designed to observe many physical quantities such as vibration, acoustic emission, noise, load torque, voltage, current, speed, and temperature, under the effect of several mechanical faults. All these features have not been used in this paper. In order to correlate all the measured physical variables at any frequency, the sampling frequency of the data acquisition system has been set to $F_s = 25$ kHz, taking into account vibration phenomena which can be detected at a maximum frequency around 10 kHz. The signals are processed under the MATLAB environment with the Welch method by an overlap of 50% and the 3-D spectrogram using the Hanning window. The resulting spectra and spectrograms are normalized using as reference magnitude the main component of the stator current and of the average torque, with everything being expressed in decibels. Two tests have been performed to hoist two loads at 300-daN (light-load) and 1000-daN (rated-load) levels for a drum speed of 1.82 rad/s.

B. Analysis and Interpretation of Measurements

With the drum rotating at 1.82 rad/s, the first test has been performed for a load of 300 daN. In this case, the induction machine rotor speed frequency is $f_r = 22.42$ Hz, and the stator current fundamental frequency is $f_s = 45$ Hz. The load torque signal at the instant when the segment of the modified wire rope is passing on the pulley between $t_{\rm in} = 10.5$ s and $t_{\rm fin} = 12.5$ s has been analyzed (Fig. 6). In this signal, it can be observed that the wire rope fault condition introduces a nonstationary load torque oscillation that can be easily identified at $f_{\rm bc} = 1.75$ Hz in the load torque spectrum (Fig. 7). In the load torque of frequency component $f_{\rm bc}$ presents a sensitivity of 9.5 dB to the



Fig. 7. Load torque spectrum in the frequency bandwidth [0 Hz, 8 Hz] for a load of 300 daN at a drum speed of 1.82 rad/s, (top) with a healthy wire rope and (bottom) with a faulty wire rope.

 TABLE I

 Observed Frequency Components in the Load Torque Spectrum for the Detection of the "Birdcaging" Effect at Light Load

		Healthy	Faulty
Frequency [Hz]		Amplitude [dB]	
f_r	22.42	-120	-116
f_{bc}	1.75	-73	-63.5

"birdcaging" effect. The magnitude of frequency component f_r shows a sensitivity of about 4 dB in the same condition (Table I). The presented test (Fig. 6) shows at the end of the load torque signal, between 22.5 and 25 s, the effect of the normal wire rope operation. This last phenomenon can be distinguished from the "birdcaging" effect because it induces other components at higher frequencies compared to the ones generated by the observed mechanical fault.

Fig. 8 shows the time–frequency analysis of the load torque signal by using the spectrogram with a healthy wire rope and a faulty wire rope. The nonstationary load torque oscillation induced by the wire rope fault can be detected at the correct instant given by the load torque signal and at the same frequency detected in the spectrum ($f_{\rm bc} = 1.75$ Hz). In the load torque spectrogram, it is also shown that, for the period for which the faulty segment of the wire rope is passing on the pulley, the magnitude of this frequency is increased by about 15 dB. In healthy condition [Fig. 8(a)], it can be observed a slight fluctuation of this last frequency component, showing the current-induced stress by the twist effect of the wire rope in healthy condition.

Fig. 9 shows the stator current spectrum for the same condition of wire rope fault. It can be observed that the effect of wire rope deformation influences the magnitudes of the frequency components $f_{\rm sbc} = f_s \pm f_{\rm bc}$ for m = 1, $f_s = 45$ Hz, and $f_{\rm bc} = 1.75$ Hz as proposed in (2). It presents a sensitivity of about 12 dB, while components depending on the rotor speed frequency $f_{\rm sr} = f_s \pm f_r$ ($f_r = 22.42$ Hz) are not sensitive (Table II).

Fig. 10 shows the stator current spectrogram for the same previous condition with the healthy wire rope and the faulty



Fig. 8. Load torque spectrogram in the frequency bandwidth [0 Hz, 10 Hz] at the instant when the segment of the modified wire rope is passing in the pulley for a load of 300 daN at a drum speed of 1.82 rad/s. (a) Healthy wire rope. (b) Faulty wire rope.



Fig. 9. Stator current spectrum in the frequency bandwidth [40 Hz, 50 Hz] for a load of 300 daN at a drum speed of 1.82 rad/s, (top) with a healthy wire rope and (bottom) with a faulty wire rope.

wire rope. It can be observed that, when the deformed wire rope is passing on the pulley, the level of the sideband frequency component given by $f_{\rm sbc} = f_s + f_{\rm bc}$ (46.75 Hz) is increased by about 10 dB from 10.5 to 12.5 s (Fig. 11). The other

TABLE II Observed Frequency Components in the Stator Current Spectrum for the Detection of the "Birdcaging" Effect at Light Load

		Healthy	Faulty
Frequency [Hz]		Amplitude [dB]	
fs-fr	22.58	-108	-110
$f_s + f_r$	67.42	-113	-111
fs-fbc	43.25	-99	-86
$f_s + f_{bc}$	46.75	-100	-88



Fig. 10. 2-D stator current spectrogram in the frequency bandwidth [40 Hz, 50 Hz] at the instant when the segment of the modified wire rope is passing in the pulley for a load of 300 daN at a drum speed of 1.82 rad/s. (a) Healthy wire rope. (b) Faulty wire rope.

sideband frequency component $f_{\rm sbc} = f_s - f_{\rm bc}$ (43.25 Hz) is not shown, but its change is almost the same (Fig. 11). In healthy condition [Fig. 11(a)], the frequency component given by $f_{\rm sbc} = f_s + f_{\rm bc}$ has a slight fluctuation as in the load torque.

The second test has been performed for a drum rotating speed of 1.82 rad/s and a load of 1000 daN. The induction machine rotor speed frequency is always $f_r = 22.42$ Hz, and the stator current fundamental frequency is not modified ($f_s = 45$ Hz). In Fig. 12, it is shown that the load torque oscillation due to the wire rope "birdcaging" effect is present between $t_{\rm in} =$ 16 s and $t_{\rm fin} = 19.5$ s. In this case, the oscillation frequency is $f_{\rm bc} = 1.73$ Hz. The torque magnitudes of the frequency



Fig. 11. 3-D stator current spectrogram in the frequency bandwidth [40 Hz, 50 Hz] at the instant when the segment of the modified wire rope is passing in the pulley for a load of 300 daN at a drum speed of 1.82 rad/s. (a) Healthy wire rope. (b) Faulty wire rope.



Fig. 12. Load torque at the drum at the instant when the segment of the modified wire rope is passing in the pulley (1000 daN of load level). (a) Signal in the time domain. (b) Time-frequency representation in the frequency bandwidth [0 Hz, 8 Hz].

components f_r and f_{bc} are shown (Table III) with a smaller value for component f_r and with a sensitivity to the "bird-caging" effect of 4 dB for component f_{bc} . Nevertheless, it is clearly observed in the spectrogram (Fig. 13) that the magnitude

TABLE III Observed Frequency Components in the Load Torque Spectrum for the Detection of the "Birdcaging" Effect at Rated Load

		Healthy	Faulty	
Frequency [Hz]		Amplitude [dB]		
f_r	22.42	-134	-128	
f_{bc}	1.73	-74	-70	



Fig. 13. Load torque spectrogram in the frequency bandwidth [0 Hz, 10 Hz] at the instant when the segment of the modified wire rope is passing in the pulley for a load of 1000 daN at a drum speed of 1.82 rad/s. (a) Healthy wire rope. (b) Faulty wire rope.

of this last frequency component has a sensitivity of 12 dB to the "birdcaging" effect.

In the stator current spectrum, frequency components $f_{\rm sr} = f_s \pm f_r$ are not at all sensitive, and frequency components $f_{\rm sbc} = f_s \pm f_{\rm bc}$ present a large sensitivity to the "birdcaging" effect of about 19 dB (Table IV). This sensitivity is also present in the stator current spectrogram (Fig. 14) on the sideband frequency components. Fig. 15 shows the frequency component at 46.73 Hz with a sensitivity of 8 dB to the wire rope fault. In healthy condition [Fig. 15(a)], the frequency component given by $f_{\rm sbc} = f_s + f_{\rm bc}$ has always a slight fluctuation as in the other cases.

By observing only the spectrogram results, the fault sensitivity of related frequency components in this last case is slightly decreased for both the load torque and the stator current. This

TABLE IV Observed Frequency Components in the Stator Current Spectrum for the Detection of the "Birdcaging" Effect at Rated Load

		Healthy	Faulty
Frequency [Hz]		Amplitude [dB]	
fs-fr	22.58	-101	-101
$f_s + f_r$	67.42	-106	-106
fs-f _{bc}	43.27	-98	-80
$f_s + f_{bc}$	46.73	-102	-82



Fig. 14. 2-D stator current spectrogram in the frequency bandwidth [40 Hz, 50 Hz] at the instant when the segment of the modified wire rope is passing in the pulley for a load of 1000 daN at a drum speed of 1.82 rad/s. (a) Healthy wire rope. (b) Faulty wire rope.

observation can be explained as a consequence of increasing the load torque. By observing the initial magnitude of the analyzed spectrograms, a threshold level can be defined around -40 dB for frequency components $f_{\rm bc}$ in the load torque and $f_s \pm f_{\rm bc}$ in the stator current. Above this given threshold which corresponds with the data acquisition system signal/noise ratio in this environment, the "birdcaging" effect can be easily recognized.

Different tests have been performed with other drum speeds, and it has been observed that the effect of "birdcaging" cannot be detected if the speed is too low even at high load levels (a speed of 0.13 rad/s with a load of 2000 daN). On the other hand, if the drum speed is high enough at a high load



Fig. 15. 3-D stator current spectrogram in the frequency bandwidth [40 Hz, 50 Hz] at the instant when the segment of the modified wire rope is passing in the pulley for a load of 1000 daN at a drum speed of 1.82 rad/s. (a) Healthy wire rope. (b) Faulty wire rope.

level (a speed of 3.3 rad/s with a load of 2000 daN), the "birdcaging" effect is well detected in both the load torque and the stator current at the same frequency components as previously explained. Therefore, there is a speed limit under which fault detection is not possible because of the sensitivity of the global system to this type of fault.

The frequency component $f_{\rm bc}$ induced in the load torque has been determined by experiment, and it clearly depends on how the wire simulating the "birdcaging" effect is wound around the main wire rope. As it is certainly related to the different dimensions of the mechanical system, it can be determined as the first torque main frequency component after 0 Hz (fundamental component for the torque).

IV. CONCLUSION

In complex electromechanical systems, a wire rope is often used as a means of mechanical force transmission. Therefore, its main mechanical fault leads to a deformation which is followed by an effect by the fleet angle on the pulley. It induces a significant increase in the torsional stress when the wire rope segment modified by the "birdcaging" effect is passing on the pulley. This torsional force is oscillatory, and it introduces a tensile stress on the wire rope load. This last phenomenon can be observed in the load torque measured at the winch drum. Many ways of detection have been proposed by mechanical engineers. In this paper, the main original contribution consists of an original way to detect this wire rope fault condition in the stator current of the electrical machine which drives the hoist winch system.

By knowing that the "birdcaging" effect affects only a little segment of the wire rope and that it introduces a nonstationary oscillation, the detection of this type of fault needs a time-frequency analysis. The results obtained with the proposed technique have shown an important sensitivity of the load torque and the stator current to the "birdcaging" effect even at different load levels and at different speeds. Therefore, it can be concluded that the time-frequency analysis of the stator current is a good indicator for the detection of the "birdcaging" effect in a wire rope associated to a hoisting winch system. It has been found that, by increasing the load torque, the resulting signal is slightly attenuated, as well as the "birdcaging" effect in the driven electrical machine stator current. However, in all cases, the fault sensitivity is between 5 and 10 dB with respect to a defined threshold which is really significant. This evaluation makes the MCSA, with a time-frequency analysis, a very efficient tool to detect "birdcaging" effects in complex electromechanical systems using wire ropes.

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