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The Low Voltage Start-up Test of Induction Motor for the Detection of Broken Bars

B. Asad, T. Vaimann, A. Belahcen , *Senior Member, IEEE*, A. Kallaste, A. Rassõlkin, H. Heidari

***Abstract*—This paper presents the broken rotor bar fault diagnostics by time-frequency analysis of motor current under extended startup transient time achieved by reducing the applied voltage. The fault diagnostics under a steady stage regime has been a topic of interest since the past few decades. The main aim has been focused on the detection of fault-based frequencies which are the function of slip. Those frequencies become very less legible under low load conditions and totally disappear under no-load conditions. Moreover, the stator and rotor slot skews have a potential attenuation impact on them. To avoid these problems, the time-frequency analysis of motor startup current is investigated in this paper using a wavelet approach. To improve the legibility of the spectrum, the transient time is extended by reducing the supply voltage of the machine under no external load. By reducing the supply voltage, the inertia of the rotor acts as a load to increase the transient time which is essential for better resolution. The results are based on the practical measurements taken from the laboratory setup under healthy and faulty conditions.**

***Index Terms*—Condition monitoring, Fault diagnosis, Fourier transforms, Induction motors, wavelet transforms.**

I. INTRODUCTION

Electrical machines have been showing their influential role in industrial and domestic applications since the second industrial revolution. This role is evident in the form of electricity generation such as wind power plants or electrical to mechanical energy converters, driving the cycles of the industry. Out of a variety of electrical machines, induction motors are being used extensively because of their simple structure, good efficiency, and easy maintenance. As a consumer, electrical machines are consuming more than fifty percent of the total energy generated worldwide.

The mechanically moving parts and rough industrial environment make ten vulnerable to the faults. The electrical faults are mainly related to the stator such as inter-turn short circuits, phase drop, voltage imbalance, earthing and inverter related faults. However, the mechanical faults are mainly associated with the rotor such as broken bars, bad bearings, eccentricity, broken end rings or bad foundations etc. All those faults are degenerative in nature which makes it very crucial to detect them at the incipient stage to avoid any catastrophic situation. A variety of fault diagnostic techniques can be found in literature, such as vibration analysis, thermal analysis, acoustic analysis, electromagnetic field inference, leakage flux, infrared light detection, and chemical analysis, etc.

However, the motor current signature analysis (MCSA) based fault diagnostic techniques are being extensively used in research, because of their noninvasive nature and least complexity. Moreover, a huge domain of data processing techniques improves their flexibility and makes them more reliable.

It is a well-studied fact that every fault modulates the stator current with a certain bandwidth of frequencies. The detection of those frequency components can lead to the cause of the fault. The Fourier transform can be considered as a foundation stone for all advanced signal processing techniques. The majority of MCSA based techniques depend on fast Fourier transform (FFT) of the signal, e.g. in [1], the authors used the FFT on active and reactive currents of a motor to investigate the broken rotor bars and load oscillations. Authors of [2] used the FFT in conjunction with Park's vector to make artificial ants clustering technique for the fault diagnostics of induction motor. In [3], the autoregressive method is relying on discrete-time Fourier transform (DTFT) and notch filter. Researchers in [4] used the FFT to prove that the slot harmonics can be used as potential indicators to detect the broken rotor bars. In [5], the authors used an adoptive notch filter and FFT for broken rotor bar fault diagnostics of induction motor. Authors of [6] used the FFT on simulations and practical results to investigate the broken rotor bars and mechanical vibrations. In [7], Nandi used the FFT extensively to study the frequency spectrum of the stator current for different fault conditions. [8] Used FFT along with a bandstop filter for the detection of broken rotor bar frequencies.

There are various limitations of FFT putting a question mark on its reliability. These limitations include the spectral leakage, which is the power of the fundamental component leaking into the subsequent frequency bins. If the length and sampling frequency of the acquired signal is not good enough, the fault representing frequency components are highly likely to be buried under the main frequency bin. This problem becomes worse when the motor is working under no-load or fewer load conditions, as the faulty frequencies are the function of the slip. The other problem of FFT is that the signal should be in a steady-state regime, stationary and should not have any discontinuities. These problems are becoming worse as the inverters are coming forward as an integral part of the drive system. The inverter fed voltage is

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full of harmonics which makes the entire frequency spectrum hazy. Moreover, the control algorithms being used in drives can also have an impact on the amplitude of harmonics. For example, in the case of direct torque control (DTC) motors, the drive has its direct influence on the current signal carrying all the information about the health of the motor [9].

Researchers have tried several different techniques to cope with those problems. The use of Hilbert transforms to extract the envelope of the signal, which, possess considerable information regarding the health of electrical machines can be found in [10]. The authors in [11] used fractional Fourier transform to recover the faulty frequencies from a non-stationary signal. In [12] authors used sliding discrete Fourier transform for the detection of broken rotor bars, while [13] [14] [15] used the wavelet technique to improve the accuracy. In this paper, a low voltage test to extend the transient interval of the motor is proposed. By increasing the transient time of the motor startup current, the time-frequency resolution of the frequency spectrum can be improved. The use of the transient interval reduces the FFT based conventional problems. All the measurements are taken without any external load to prove the effectiveness of the method. The wavelet transform is preferred over short-time Fourier transform (STFT) to avoid inherited FFT drawbacks. Moreover, a band stop infinite impulse response (IIR) filter is used to attenuate the fundamental component which improves the legibility of the spectrum.

II. Theoretical Background

A. Modulation of Fault

The phase current of an ideal and symmetrical machine can be described as:

$$i_a(t) = I_m sin(\omega t + \alpha) \tag{1}$$

where I_m is the peak current, ω is supply frequency and α is the phase angle. The unsymmetrical rotor with broken rotor bars, broken end rings or bad bearings starts modulating the current with a frequency-dependent upon the speed of the rotor and the modulation index depending upon the severity of the fault.

$$i_{af}(t) = [1 + m(t)]i_a(t) \tag{2}$$

where $m(t)$ is the modulating signal, having a modulation index M, which depends on the number of broken bars (Nb) and the total number of rotor bars (Nt). If the rotor is rotating and the winding distributions are considered as sinusoidal, the modulating signal is also a sinusoid, i.e.:

$$m(t) = Mcos(\omega_o t + \phi) \tag{3}$$

where $\omega_o = 2\pi f_o$, is the fault characteristic frequency and depends upon the nature of the fault and the slip of the machine. In case of broken rotor bars, the characteristic fault frequency is at $2sf_s$:

$$f_o = 2sf_s \quad and \quad \omega_o = 2\pi(2sf_s) \tag{4}$$

$$m(t) = Mcos(4\pi sf_s t + \phi) \tag{5}$$

$$i_{af}(t) = [1 + Mcos(4\pi sf_s t + \phi)]i_a(t) \tag{6}$$

$$i_{af}(t) = [1 + Mcos(4\pi sf_s t + \phi)]I_m sin(\omega t + \alpha) \tag{7}$$

$$i_{af}(t) = I_m sin(2\pi sf_s t)(\frac{MI_m}{2})[sin(2\pi f_s(1+2s)t + \phi + \alpha) + sin(2\pi f_s(1-2s)t + \phi + \alpha)] \tag{8}$$

where the modulation index M can be approximated as a ratio of the number of broken rotor bars and the total number of bars as in [16]

$$m \approx \frac{N_b}{N_t} \tag{9}$$

B. The Fast Fourier Transform

Being able to segregate any stationary signal into its frequency components, Fourier transform can be considered as a foundation stone of conventional and advanced signal processing based fault diagnostic techniques. A very good overview and history of Fourier transform can be found in [17]. The discrete Fourier transform (DFT) shown by (10) can convert a signal of finite length represented by a finite number of equally spaced samples to a signal of the same length represented by equally spaced frequency bins. The DFT can be solved with less computational complexity using an algorithm called Fast Fourier transform (FFT).

$$X_n = \sum_{n=0}^{N-1} x_n e^{-i2\pi kn/N}, \quad k = 0, 1, 2, ..., (N-1) \tag{10}$$

where x_n, is the discrete sampled signal and N is the number of samples, which should be a number in power of 2, i.e. $N = 2x$ to reduce the computational time and spectral leakage. The frequency resolution is very important in various signal processing techniques in order to detect weak faulty harmonics. It can be defined as the separation between two consecutive frequency bins. The least the difference is, the better the resolution could be. It depends upon the sampling frequency and measurement length of the signal as shown by the following equations.

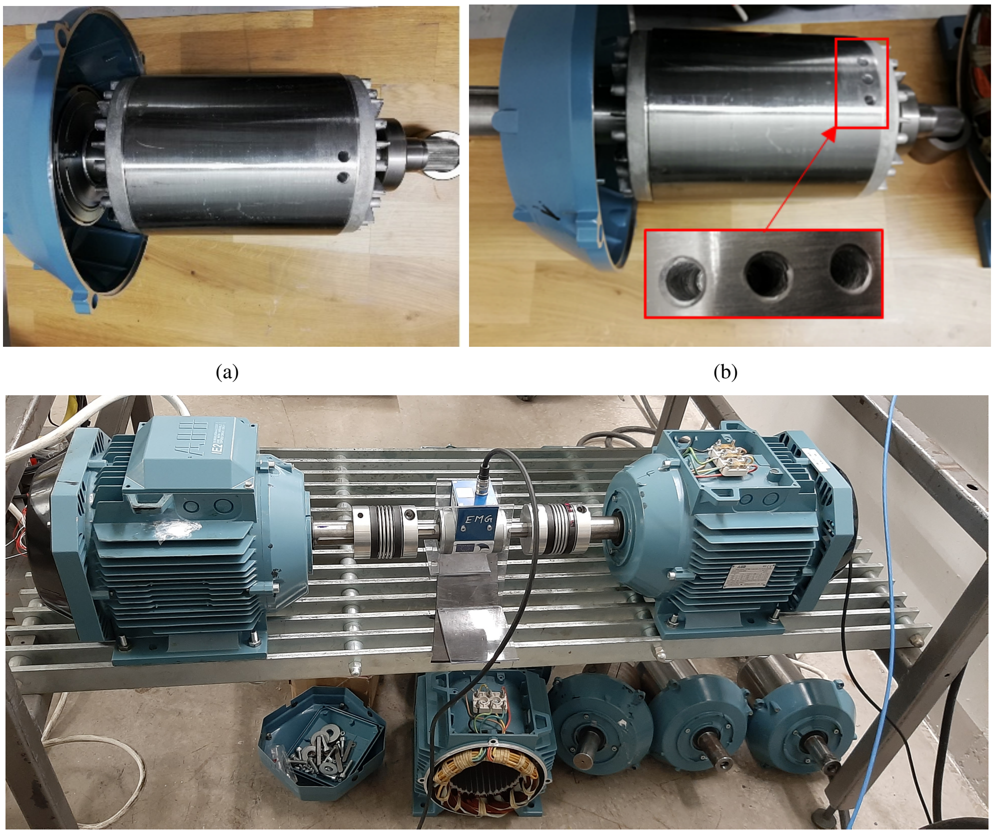
$$t_{sig} = t_s \times N = N/f_s \tag{11}$$

$$df = 1/t_{sig} = f_s/N = BW/SL \tag{12}$$

$$SL = N/2 \tag{13}$$

where df is the frequency resolution, f_s is the sampling frequency, BW is the bandwidth, SL is the number of spectral lines, t_{sig} is the measurement or acquisition time of the signal and N is the number of data points used in FFT or the total number of samples. It is evident that frequency resolution can only be increased by increasing the measurement time, also called the acquisition or frame time, of the signal. Frequency resolution can also be increased by zero paddings of the signal called the spectral interpolation.

The prominent drawbacks of DFT for fault diagnostics can be described as. It is unable to deal with non-stationary signals. The high sampling rate and increased length of the



(a) (b)

(c)

Fig. 1. The test rig preparation (a) The rotor with two broken bars, (b) The rotor with three broken bars, (c) The test bench with loading motor on right side and test motor on left side.

signal increase the complexity of the diagnostic algorithm. The discontinuities in the signal can lead to wrong results. The small faulty frequencies always remain vulnerable to be buried under some strong frequency components due to their spectral leakage. Moreover, it cannot give any time-frequency spectrum of the signal, which is very essential while handling non-stationary signals such as in the transient regime. The motor's slip changes rapidly during startup or shut down transient intervals of the motor operation. This fact can be exploited to detect faults under a transient regime with improved legibility. It can be done by using the short-time Fourier transform (STFT), where the complete signal is divided into n small segments. Each segment is considered as stationary and its DFT is calculated using the FFT algorithm. This approach gives the time-frequency representation of the signal but at the cost of increased complexity and inherited drawbacks of the FFT algorithm. Moreover, the selection of different types of windows is very important for different types of signals.

C. Wavelet Transform

The above-mentioned problems of DFT and STFT can be minimized using the wavelet approach. In this approach, a window of some predefined frequency and amplitude is swiped across the entire signal to see where it closely matches the signal. This window is called mother wavelet while its frequency is saved as scale a and position by b. The resultant cwt coefficients $X_w(a,b)$, contains the time-frequency information of the signal as shown by (14). The signal can be reconstructed using these coefficients by taking the inverse wavelet transform. The process is repeated several time to detect different frequency components at different times.

$$X_w(a,b) = \frac{1}{|a|^{1/2}} \int_{-\infty}^{\infty} x(t)\bar{\psi}\left(\frac{t-b}{a}\right) dt \qquad (14)$$

The legibility of the frequency spectrum in either steady-state or transient regime depends upon the length of the signal. The slip of the motor defines the position of the faulty frequency components as described in the previous equations. During the transient interval, the slip is not constant but decreases with an increase in speed as the motor goes towards a steady-state regime. This change in the slip can develop some specific patterns in the time-frequency spectrum. Most of the time, this transient interval is so small that those patterns do not become visible. This fact becomes even worse when the motor operates at low load conditions. In this paper, this transient interval is extended by decreasing the supply voltage. By doing so, the inertia of the rotor can be used to control the transient time of the motor.

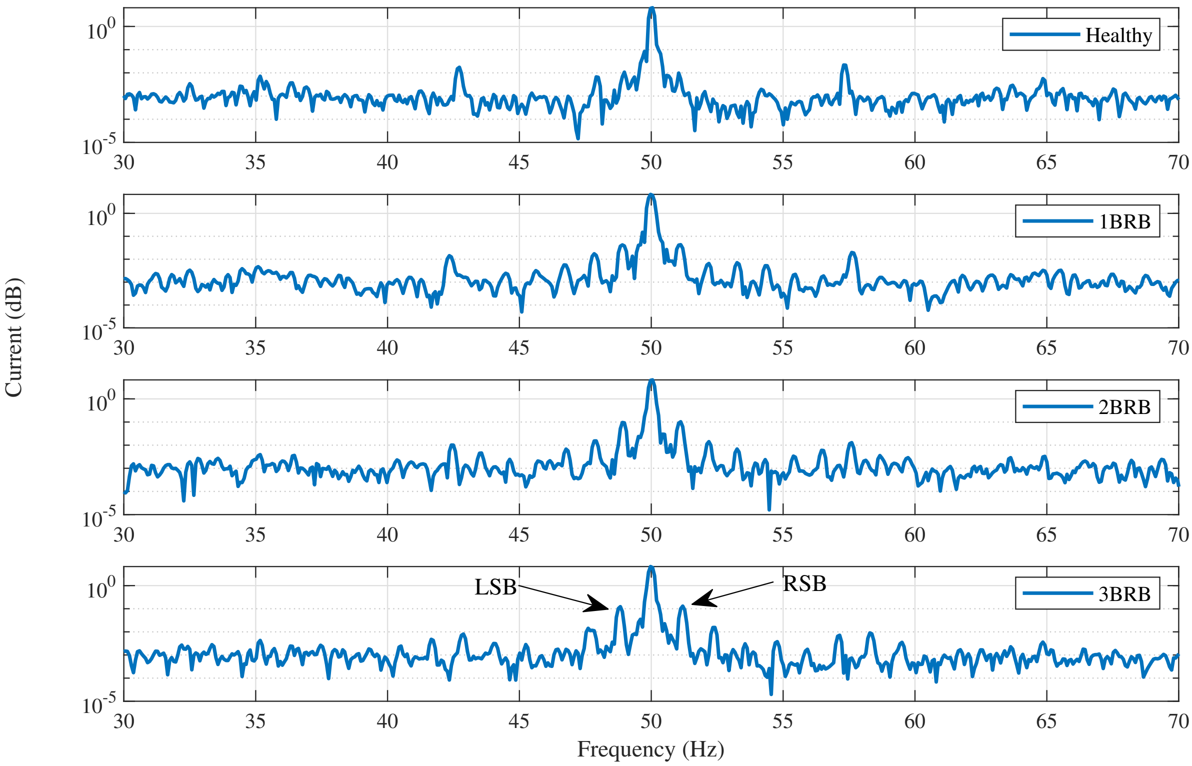


Fig. 2. The frequency spectrum from 30 Hz to 70 Hz showing the development of faulty frequency components.

III. Practical Setup

The test rig consists of a motor under investigation attached with a loading machine, the three-phase variable transformer and data acquisition setup. The motor with specifications given in Table I, is tested with healthy and broken bar-based rotors. The bars are broken by drilling radial holes having a depth equal to the total rotor slot height. The motor phase currents are measured under transient intervals using the Dewetron transient recorder. The sampling frequency of the measured signal is 10000 Hz, which is enough for better resolution as the machine is grid fed. The test setup is shown in Fig. 1.

TABLE I
THE MACHINE SPECIFICATIONS.

Parameter	**Symbol**	**Value**
Number of poles	P	4
Number of phases	ϕ	3
Connection	-	Delta
Stator slots	N_s	36; Non-skewed
Rotor slots	N_r	28; skewed
Rated voltage	V	400V@50 Hz
Rated current	I	8.8A
Rated power	P_r	7.5 kW@50 Hz

IV. Results and Discussion

The frequency spectrum of stator current under healthy and broken rotor bars at rated load condition is shown in Figs. 2 and 3. The spectrum in Fig. 2 shows the evolution of left side band (LSB) and right-side band (RSB)harmonics. These harmonics are the function of slip and the results are based

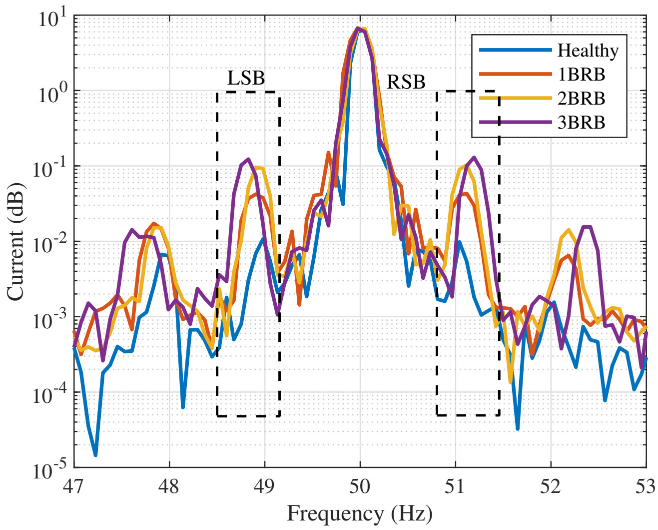


Fig. 3. The development of lest side band (LSB) and right side band (RSB) frequencies with the increase in the number of broken bars.

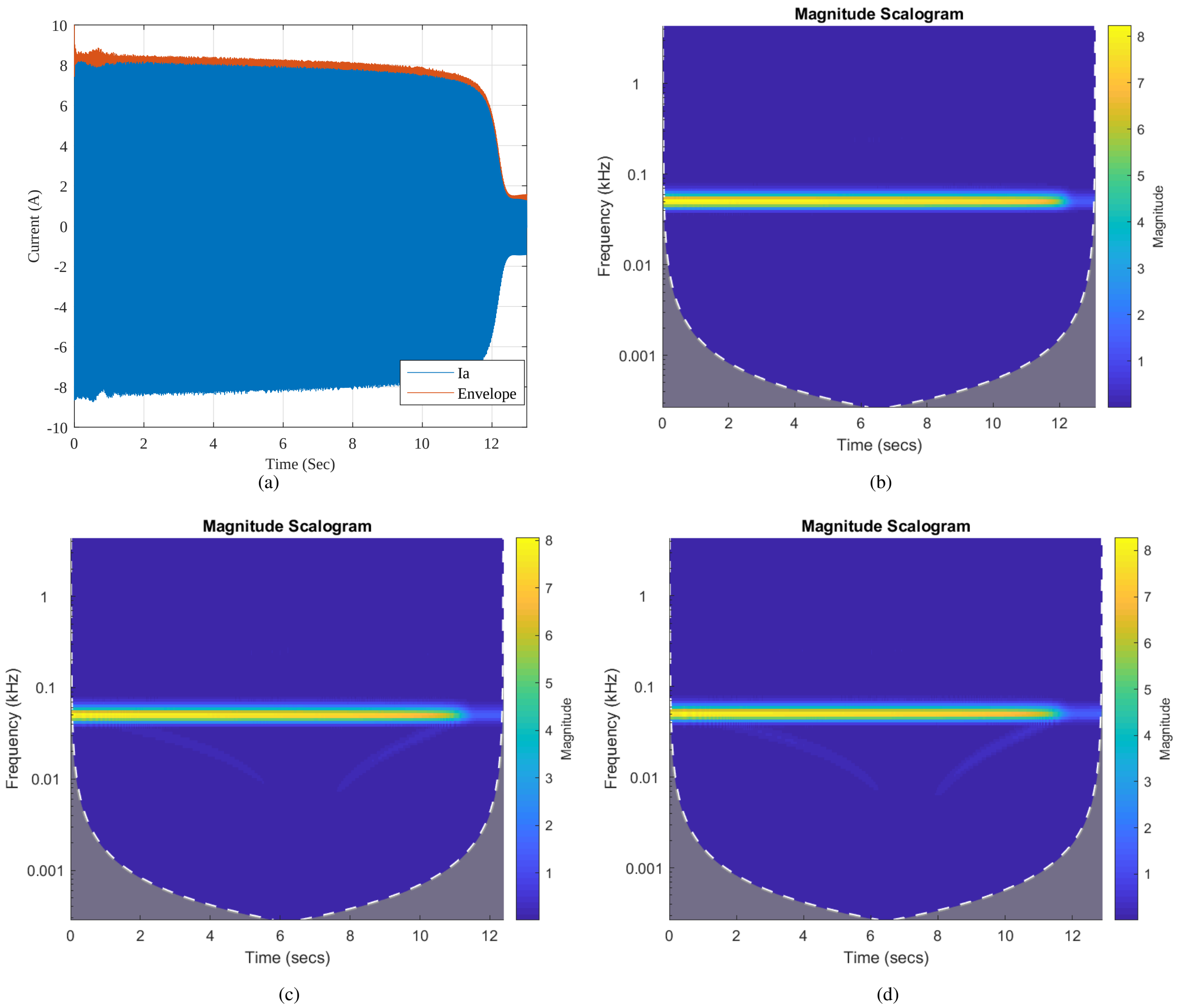


Fig. 4. (a) Motor's phase current and corresponding envelope under transient regime, (b) Time-frequency spectrum in healthy case, (c) Time-frequency spectrum in 1 broken bar case, (d) Time-frequency spectrum in 2 broken bars case.

on the measurements taken under rated load condition. It is evident that the side-band frequencies increase in amplitude with the increase in the number of broken bars. In addition, the side-band fault frequencies tend to shift slightly away from the fundamental component with the increase in the number of bars as shown in Fig.3. This is because with the increase in the number of broken bars the average generated torque decreased with a slight increase in slip. The legibility of these harmonics is very poor, and it is very difficult to segregate them from the rest of the harmonics as shown in Fig. 2. The severity of this problem increases with the decrease in load. As the load decreases, these harmonics start hiding under a strong fundamental component with a total disappearance at no-load condition. Moreover, the skewness in the rotor and stator slots affects their amplitude making them less detectable at the incipient stage. It is also important to mention that these harmonics also remain venerable when the inverter feeds the motor. This effect can be in the form of a huge number of harmonics being fed by the inverter, which makes faulty frequencies even more difficult to be segregated. Moreover, the impact of the drive controller cannot be ignored. This impact is severed in the case of DTC controlled motors, where the controller of drive tries to eliminate the current harmonics to reduce torque ripples [9].

To avoid all those problems, the inspection of motor current under the transient regime shows promising results. In order to increase the transient time for better time-frequency resolution, the supply voltage can be reduced. Several experiments are performed at 15%, 25%, 50%, 75%, and 100% of nominal voltage without external load. By reducing the voltage the inertia of the motor's rotor acts as a load and increases the transient time. With the increase in the applied voltage, the motor takes less time to reach a steady-state inter-

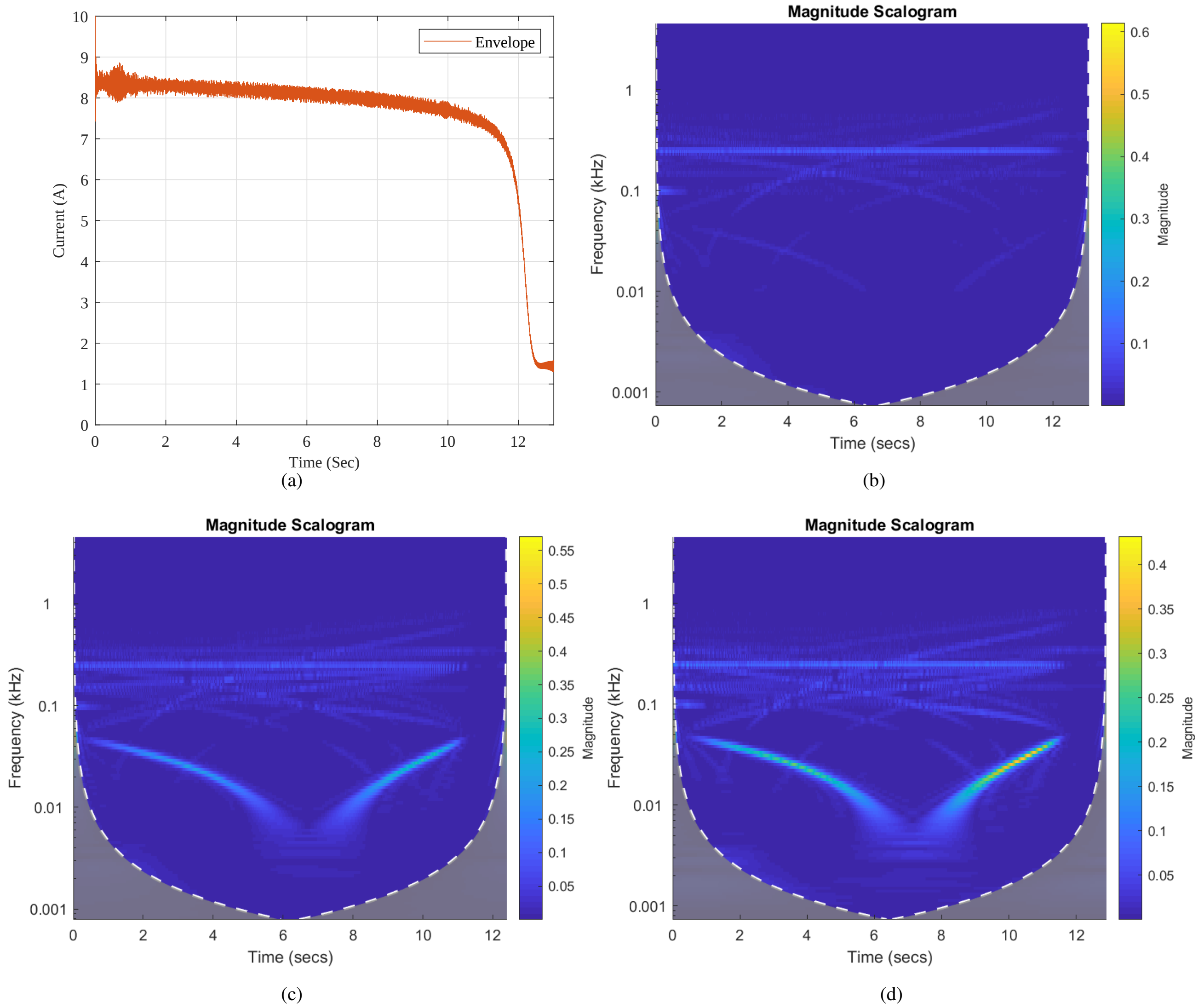


Fig. 5. (a) The envelope of motor's phase current in transient regime, (b) Time-frequency spectrum in healthy case with attenuated fundamental component, (c) Time-frequency spectrum in 1 broken bar case with attenuated fundamental component, (d) Time-frequency spectrum in 2 broken bars case with attenuated fundamental component.

val. Under the transient regime, the continuously decreasing slip moves the RHS and LHS frequency components towards fundamental components. This makes a V-shaped pattern whose width depends upon the transient time as shown in Fig. 4 where the supply voltage is 15% of the nominal voltage. This pattern is not well legible because the sideband frequencies are very small in amplitude as compared to the fundamental component. This pattern can be made very clear by attenuating the fundamental component as shown in Fig. 5. The infinite impulse response (IIR) bandstop filter is used to remove the fundamental component.

V. Conclusions

The broken rotor bars fault diagnostics by time-frequency analysis of motor current under transient period is investigated in this paper. The detection of fault frequencies in the steady-state interval is very common in literature but possesses several difficulties. Since the sideband frequencies are the function of slip, they become very difficult to discover under low load conditions. The spectral leakage of the powerful supply components is very dangerous for the visibility of faulty components as they are very weak in amplitude. This spectral leakage is also the function of signal length, the sampling frequency and the type of the window used to compute FFT.

Moreover, the inclusion of a huge bandwidth of inverter fed frequencies makes the detection of faulty frequencies hazier. The impact of the drive controller to reduce the current ripples is another fact, which makes the fault diagnostic under a steady-state regime difficult.

These drawbacks can be resolved by investigating the health in the transient regime. The biggest drawback of the transient interval is a minor time, which reduces the resolution of the spectrum. This transient time can be increased by reducing the applied voltage without any external load. By doing so the broken bars based v-shaped pattern can be seen with great accuracy. Moreover, the FFT based drawbacks are considerably reduced by using the wavelet approach. The legibility of the transient spectrum is further enhanced by attenuating the fundamental component with the help of an IIR filter.

The IIR bandstop filter has a sharp transition interval and low passband ripples having less impact on the remaining frequency components. The results are validated using the measurements taken from a laboratory-based test rig.

REFERENCES

[1] G. Bossio, C. De Angelo, J. Bossio, C. Pezzani, and G. Garcia, "Separating Broken Rotor Bars and Load Oscillations on IM Fault Diagnosis Through the Instantaneous Active and Reactive Currents," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4571–4580, Nov. 2009.

[2] A. Soualhi, G. Clerc, and H. Razik, "Detection and Diagnosis of Faults in Induction Motor Using an Improved Artificial Ant Clustering Technique," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 9, pp. 4053–4062, Sep 2013.

[3] B. Ayhan, H. Trussell, Mo-Yuen Chow, and Myung-Hyun Song, "On the Use of a Lower Sampling Rate for Broken Rotor Bar Detection With DTFT and AR-Based Spectrum Methods," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 1421–1434, Mar 2008.

[4] A. Khezzar, M. Kaikaa, M. El Kamel Oumaamar, M. Boucherma, and H. Razik, "On the Use of Slot Harmonics as a Potential Indicator of Rotor Bar Breakage in the Induction Machine," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4592–4605, Nov. 2009.

[5] M. Malekpour, B. T. Phung, and E. Ambikairajah, "Stator current envelope extraction for analysis of broken rotor bar in induction motors," in *2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*. IEEE, Aug 2017, pp. 240–246.

[6] A. Belahcen, J. Martinez, and T. Vaimann, "Comprehensive computations of the response of faulty cage induction machines," in *2014 International Conference on Electrical Machines (ICEM)*. IEEE, Sep 2014, pp. 1510–1515.

[7] S. Nandi, H. Toliyat, and X. Li, "Condition Monitoring and Fault Diagnosis of Electrical Motors—A Review," *IEEE Transactions on Energy Conversion*, vol. 20, no. 4, pp. 719–729, Dec. 2005.

[8] B. Asad, T. Vaimann, A. Kallaste, and A. Belahcen, "Harmonic Spectrum Analysis of Induction Motor With Broken Rotor Bar Fault," in *2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*. IEEE, Nov. 2018, pp. 1–7.

[9] B. Asad, T. Vaimann, A. Belahcen, A. Kallaste, A. Rassõlkin, and M. N. Iqbal, "Broken rotor bar fault detection of the grid and inverter-fed induction motor by effective attenuation of the fundamental component," *IET Electric Power Applications*, Jul. 2019.

[10] R. Puche-Panadero, M. Pineda-Sanchez, M. Riera-Guasp, J. Roger-Folch, E. Hurtado-Perez, and J. Perez-Cruz, "Improved Resolution of the MCSA Method Via Hilbert Transform, Enabling the Diagnosis of Rotor Asymmetries at Very Low Slip," *IEEE Transactions on Energy Conversion*, vol. 24, no. 1, pp. 52–59, Mar. 2009.

[11] M. Pineda-Sanchez, M. Riera-Guasp, J. A. Antonino-Daviu, J. Roger-Folch, J. Perez-Cruz, and R. Puche-Panadero, "Diagnosis of Induction Motor Faults in the Fractional Fourier Domain," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 8, pp. 2065–2075, Aug. 2010.

[12] M. A. Moussa, M. Boucherma, and A. Khezzar, "A Detection Method for Induction Motor Bar Fault Using Sidelobes Leakage Phenomenon of the Sliding Discrete Fourier Transform," *IEEE Transactions on Power Electronics*, vol. 32, no. 7, pp. 5560–5572, Jul. 2017.

[13] S. Kia, H. Henao, and G.-A. Capolino, "Diagnosis of Broken-Bar Fault in Induction Machines Using Discrete Wavelet Transform Without Slip Estimation," *IEEE Transactions on Industry Applications*, vol. 45, no. 4, pp. 1395–1404, Jul. 2009.

[14] S. Singh and N. Kumar, "Detection of Bearing Faults in Mechanical Systems Using Stator Current Monitoring," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 3, pp. 1341–1349, Jun. 2017.

[15] M. Kang and J.-M. Kim, "Reliable Fault Diagnosis of Multiple Induction Motor Defects Using a 2-D Representation of Shannon Wavelets," *IEEE Transactions on Magnetics*, vol. 50, no. 10, pp. 1–13, Oct. 2014.

[16] A. Bellini, F. Filippetti, G. Franceschini, C. Tassoni, and G. Kliman, "Quantitative evaluation of induction motor broken bars by means of electrical signature analysis," *IEEE Transactions on Industry Applications*, vol. 37, no. 5, pp. 1248–1255, 2001.

[17] M. T. Heideman, D. H. Johnson, and C. S. Burrus, "Gauss and the history of the Fast Fourier Transform," *IEEE Acoustics, Speech, and Signal Processing Magazine*, vol. 1, no. October, pp. 14–21, 1984.

VI. BIOGRAPHIES

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