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Hilbert Transform Demodulation for Distinguishing Broken Rotor Bars and Load Oscillations in Induction Motors

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***Abstract*— Accurately distinguishing between broken rotor bar (BRB) faults and load torque oscillations in induction motors remains a significant diagnostic challenge, especially under low or variable load conditions where both phenomena generate overlapping spectral components in the stator current. To address this limitation, this work proposes a simplified offline diagnostic approach based on Hilbert transform demodulation of the stator current. The method extracts instantaneous amplitude and phase modulation signals, which are then analyzed in the frequency domain using the Fast Fourier Transform (FFT). Experimental tests were performed on two machines—one with an intentionally induced BRB fault and another subjected to controlled load oscillations between 400 W and 600 W. The obtained demodulated signatures were compared with classical Motor Current Signature Analysis (MCSA). The results demonstrate that BRB faults predominantly produce amplitude modulation at 2sfs, whereas load torque oscillations induce both amplitude and significant phase modulation at the oscillation frequency. A two-dimensional representation of the modulation indices provides a clear separation between the two types of disturbances. The proposed Hilbert-based demodulation approach therefore offers a robust, interpretable, and more reliable diagnostic tool than conventional MCSA under variable load conditions.**

***Keywords*— Induction machine; Broken rotor bars defects; Load oscillation over time; Motor Current Signature Analysis (MCSA); Phase and amplitude modulation signal; Hilbert transform.**

I. Introduction

Fault diagnosis in asynchronous machines is essential to prevent unexpected breakdowns and costly downtimes. This task becomes particularly challenging under low-load operation, varying loads, or when the supply is distorted by inverter harmonics [1]– [3]. A fault in an induction motor can manifest through noise, vibration, heating, or changes in electrical signals such as current, voltage, torque, and speed [4].

Diagnostic techniques are commonly classified into two groups: signal-based methods, which rely on processing machine signals in the time or frequency domain, and model-based approaches, which use mathematical representations of the machine [5]– [6]. Among signal-based methods, Motor Current Signature Analysis (MCSA) is widely adopted because it requires only current sensors already available in most installations [7], [8]. While effective at rated load, its performance deteriorates when the machine operates at low slip, under fluctuating load, or in the presence of supply harmonics. These conditions make it difficult to separate fault-related spectral components from those introduced by load oscillations. To address these limitations, advanced signal processing techniques have been investigated, including wavelet transforms, Short-Time Fourier Transform (STFT), and power spectral density analysis [9]– [10]. Although effective in certain cases, these approaches face drawbacks such as limited resolution, sensitivity to noise, or the need for prior knowledge of fault frequencies [11]– [13]. In particular, load torque oscillations occurring at multiples of the rotational speed can strongly affect the stator current spectrum. When their frequency coincides with the fault frequency, the resulting sideband harmonics overlap, complicating diagnostics [14]– [15]. Therefore, an alternative approach is required to separate fault effects from load-induced oscillations.

In this work, we propose a simplified method based on the Hilbert transform applied to the stator current. By extracting instantaneous amplitude and phase modulation signals, and analyzing them in the frequency domain, it becomes possible to distinguish broken rotor bar faults (mainly amplitude modulation) from load torque oscillations (both amplitude and phase modulation). Experimental results on induction machines with

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induced bar faults and controlled load variations confirm the effectiveness of the proposed method compared to traditional MCSA. The rest of this paper is organized as follows: Section 2 reviews The Amplitude and phase modulation of stator current in the case of broken rotor bar and load oscillation. Section 3 and 4 describes single three phase stator current demodulation respectively. Section 5 Description of The Experimental Test Bench. Discuss The Results of The Experiment is described in Section 6. Finally, a conclusion is presented in Section 7.

II. STATOR CURRENT AMPLITUDE AND PHASE MODULATION

Fault diagnosis based on stator current relies on correctly attributing measured spectral components to either electrical faults (e.g. broken rotor bars) or mechanical/load phenomena (e.g. torque oscillations). This section presents the essential physical mechanisms that generate amplitude and phase modulation in the stator current and gives the compact expressions used later for demodulation with the Hilbert transform.

A. Broken Rotor Bar Effect

A rotor bar crack breaks the rotor symmetry and produces a backward rotating magnetomotive force (MMF). In the Stator reference frame this introduces sideband components located at $(1\pm2s)\, f_s$, where s is slip and fs the supply frequency [10]. Retaining the dominant carrier at f_s and the two main sidebands, the stator current may be approximated by:

$$i_{sf}\ (t) = I_s\ cos(\omega_s\ t) + I_L\ cos((1-2s)\ \omega_s\ t) + I_U\ cos((1+2s)\ \omega_s\ t) \quad (1)$$

with $\omega_s=2sf_s$. Using trigonometric identities and the common case IL ≈ IU, the sideband pair can be recast as an amplitude modulation of the carrier:

$$i_{s\,f}\ (t) = I_s\ cos(\omega_s\ t) + I_L\ cos((1-2s)\ \omega_s\ t) \quad (2)$$

This explicit form shows that broken-bar faults produce a dominant amplitude modulation (AM**)** of the stator current with modulation frequency $2sf_s$. The amplitude modulation index is proportional to the Lower and upper sideband amplitudes I_L, I_U and increases with fault severity and load.

B. Effect of Load Torque Oscillations

Mechanical disturbances such as unbalance, transmission defects, or periodic external loads produce oscillating load torque at the characteristic fault frequency f_c. The load torque can be expressed as [15]:

$$\Gamma_c = \Gamma_0 + \sum_{k=1}^{\infty} \Gamma_k . \cos(k.\omega_c.t) \quad (3)$$

where Γ_k is the amplitude of the k harmonic, and $\omega_c=2\pi f_c$. Considering only the fundamental component, the mechanical equation yields the rotor speed perturbation:

$$\omega_r(t) = -\frac{\Gamma_{osc}}{J.\omega_c} . \sin(\omega_c.t) + \omega_{r0} \quad (4)$$

with J being the total inertia. The rotor position can be determined by integrating the rotor rotation speed given by the previous equation (5).

$$\theta_r(t) = \int_{t_0}^{t} \left[-\frac{\Gamma_{osc}}{J.\omega_c} . \cos(\omega_c.t) + \omega_{r0} \right] .dt = \frac{\Gamma_{osc}}{J.\omega_c^2} . \cos(\omega_c.t) + \omega_{r0}.t + \theta_{r0} \quad (5)$$

assuming $\theta r(t_0)$ =0. For a healthy motor, the rotor position is $\omega_{r0}t$, whereas in the presence of torque oscillations an additional oscillatory term appears, depending on f_c. These oscillations induce phase modulation (PM) in the rotor magnetic field, expressed in the stator reference frame. The modulation index depends on inertia J, torque amplitude Γc, and oscillation frequency f_c. As a result, the stator current can be represented as a sinusoidal component at frequency f_s with both amplitude and phase modulations at f_c [4]:

$$I_{osc}(t) = I_s . \cos(\omega_s.t) + I_r . \left(1 + \frac{p.\Gamma_{osc}}{J.\omega_c} . \sin(\omega_c.t) \right) . cos\left(\omega_s t - p\varphi_{se} - \frac{p.\Gamma_{osc}}{J.\omega_c^2} . \cos(\omega_c.t) \right) \quad (6)$$

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Therefore, two observations follow and motivate the demodulation approach used in this paper. Broken rotor bars generate a strong amplitude modulation (AM) component at the frequency $2sf_s$, while the associated phase modulation (PM) remains comparatively weak under identical operating conditions. In contrast, load torque oscillations produce significant PM (and often secondary AM) at the oscillation frequency f_c. When f_c (or its harmonics) coincides with the fault-related sideband frequencies $(1\pm2s)\ f_s$, classical spectrum analysis (MCSA) cannot reliably distinguish between fault-induced and load-induced components.

Because the current stator becomes non-stationary in such situations, direct Fourier analysis provides ambiguous results. Demodulation techniques that separately extract the instantaneous amplitude and phase [7], [9], and then analyze their spectra, offer a more robust discrimination. In this work, the Hilbert transform is applied to the measured stator current to obtain the analytic signal:

$$z(t) = \left[i(t) + j\ Hilbert\left(i(t)\right) \right] = a(t)\ e^{j\phi(t)} \tag{7}$$

where $a(t)=|z(t)|$ is the instantaneous amplitude and $\varphi(t)=arg(z(t))$ is the instantaneous phase. The amplitude spectrum of a(t) highlights fault-related modulations, while the spectrum of $\varphi(t)$ emphasizes load-induced oscillations. To enhance interpretability, a two-dimensional representation is introduced, with amplitude modulation plotted on the x-axis and phase modulation on the y-axis. This mapping can clearly separate broken-bar faults from load torque oscillations, compared to fixed-window STFT or classical MCSA, this approach provides improved separation of AM and PM contributions and facilitates a straightforward interpretation of the modulation indices [18].

III. Experimental Setup For Load Torque Variation Testing

To evaluate the proposed diagnostic strategy under reproducible conditions, a dedicated test bench was implemented, allowing the controlled generation of both mechanical load oscillations and rotor bar faults. The experimental tests were carried out in the laboratory using a 3 kW, 220/380 V, 50 Hz, three-phase squirrel-cage induction motor mechanically coupled to a 1.5 kW DC generator. The generator served as a controllable load, enabling both steady and oscillating torque conditions. To emulate load oscillations, the generator was connected to two resistor banks. The first bank was manually adjustable through switches, while the second was linked to an IGBT-based electronic switch controlled by a function generator.By modulating the switching frequency and duty cycle, periodic load variations were introduced in the range of 400 W to 600 W. This setup reproduced realistic operating scenarios with oscillating torque at a predefined frequency. Current and voltage signals from the induction motor were acquired using a DaqBoard/3000USB acquisition system with 16-bit resolution and a maximum sampling rate of 1 MHz. The acquired data were processed in MATLAB to extract the analytic signal via the Hilbert transform and to perform subsequent demodulation and spectral analysis. This experimental configuration provides a controlled environment to compare the signatures of broken rotor bar faults and load torque oscillations under reproducible conditions.

A. Effect of Load Variation on the spectrum of the stator current

As shown in Section II, load torque oscillations induce both amplitude and phase modulation in the stator current. When the load varies at a frequency f_c, sideband components appear at $(f_s\pm f_c)$. If f_c is of the same order as $2sf_s$, these components may overlap with those produced by a broken rotor bar, complicating fault diagnosis. Figure 1 presents the stator current spectrum for load variations between 400 W and 600 W, and between 2000 W and 2200 W, at an oscillation frequency of 3 Hz. In both cases, sidebands at $(f_s\pm kf_c)$ are clearly observed. The left sideband amplitude is higher than the right due to phase shift effects. With increasing load, the position of the sidebands remains unchanged, but their amplitudes grow significantly. For comparison, Figure 2 shows the spectrum obtained when two rotor bars are broken under high load. Similar sideband harmonics are visible, with localization and amplitude depending on both load level and fault severity. This overlap between sidebands caused by torque oscillations and those caused by rotor bar faults demonstrates the limitation of classical spectrum analysis: it cannot reliably separate the two phenomena. To overcome this difficulty, demodulation techniques are employed. In this work, the Hilbert transform is applied to isolate amplitude and phase modulations, providing a reliable separation of rotor faults from load-induced oscillations.

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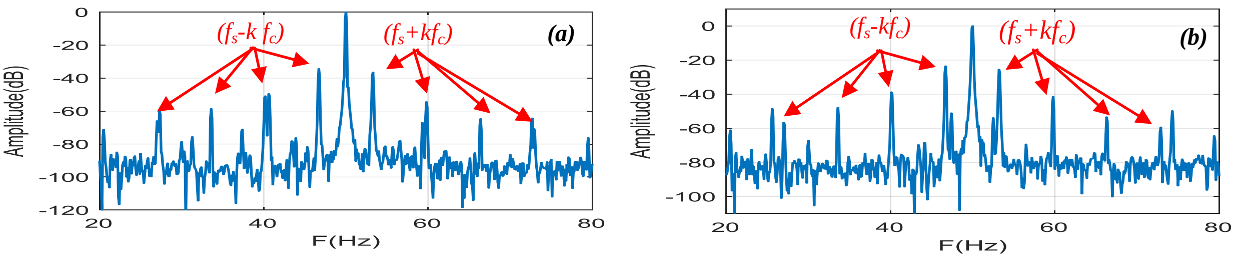

Fig. 1. Spectral analysis of stator current for: (a) load varies between 400W and 600W, (b) load varies between 2000W and 2200W.

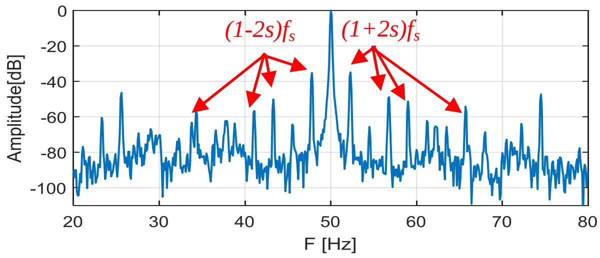

Fig. 2. Spectral analysis of stator current for a breaking of two rotor bars under high load.

B. Separation Between Load Variation and Rotor Bar Fault Using the Hilbert Transform

To analyze the modulation phenomena in the stator current, the Hilbert transform was applied to generate the analytic signal from the measured current. Using MATLAB toolboxes, the analytic signal was formed, and the instantaneous amplitude and phase were extracted. The instantaneous amplitude was directly obtained from the modulus of the analytic signal. The instantaneous phase, expressed as $\omega st - \beta\cos(\omega ct)$, includes a linear component due to the supply frequency. To isolate only the modulation, this linear part was removed by polynomial fitting. Specifically, the polyfit() function was used to estimate the best first-order polynomial approximation, and polyval() was used to evaluate and subtract it. The resulting signal corresponds to the pure phase modulation, as illustrated in Fig. 3(c). Figure 4 presents the spectra of the instantaneous amplitude and phase for the case of load torque oscillation. Both amplitude and phase modulations are clearly visible, with the phase modulation exhibiting the dominant contribution. The same procedure was applied to the current of a machine with a broken rotor bar operating under high load. The corresponding results are shown in Fig. 5, with the spectra in Fig. 6. In this case, amplitude modulation is clearly dominant, while phase modulation appears with very low amplitude, confirming the theoretical expectations.

To enhance visualization, the amplitudes of the two modulation types were represented in a two-dimensional plane, with amplitude modulation on the x-axis and phase modulation on the y-axis. The results are shown in Fig. 7. Red markers correspond to the machine with a rotor bar fault, while blue markers correspond to the machine under load oscillation. The clear clustering of points in different regions demonstrates the ability of the Hilbert-based method to separate the two phenomena effectively.

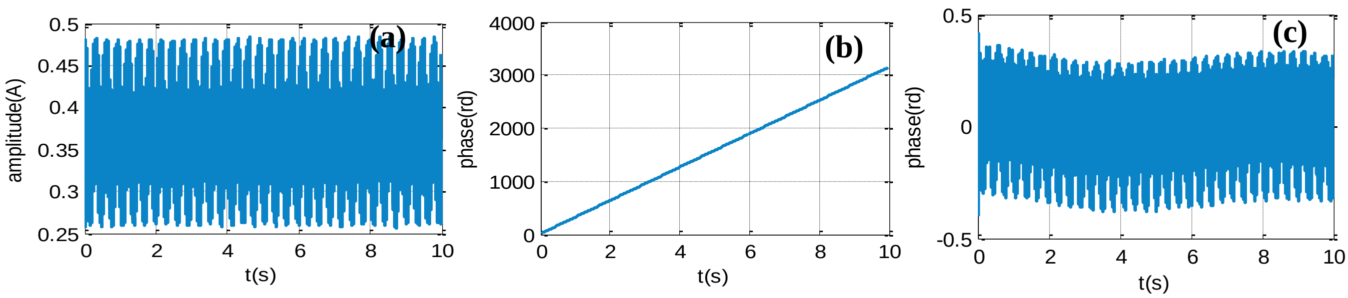

Fig. 3. Extraction of Instantaneous Amplitude and Phase using the Hilbert Transform for a Load Variation between 400W and 600W: (a) Amplitude, (b) Instantaneous Phase, (c) Removal of the Linear Component.

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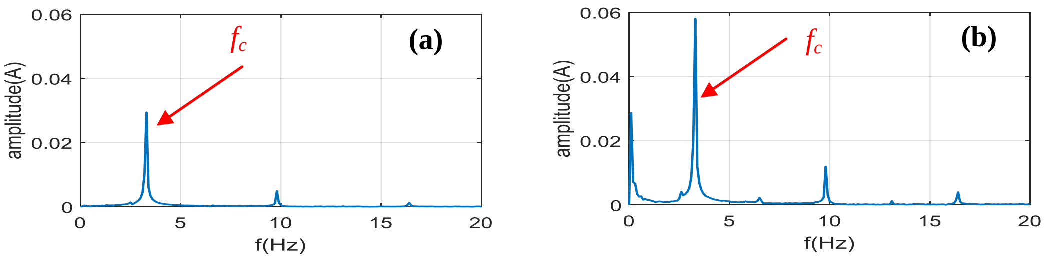

Fig. 4. Spectra of amplitude (a) and phase (b) for the case of load torque oscillation between 400W and 600W.

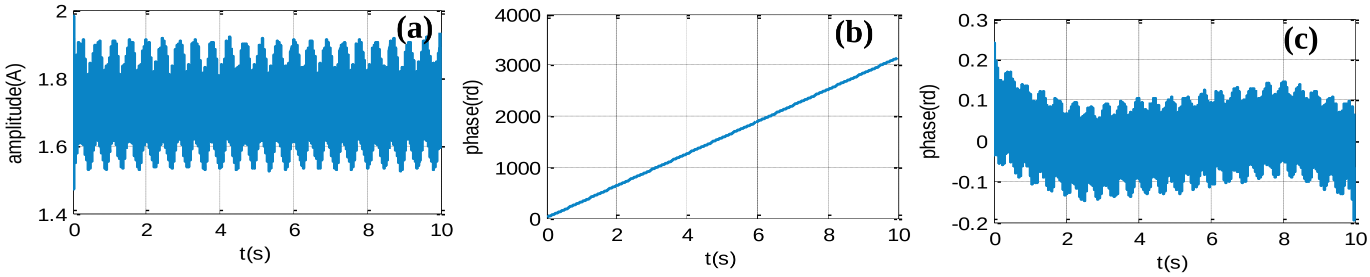

Fig. 5. Extraction of instantaneous amplitude and phase by Hilbert transform for a broken rotor bar fault: (a) amplitude, (b) phase, (c) elimination of the linear component.

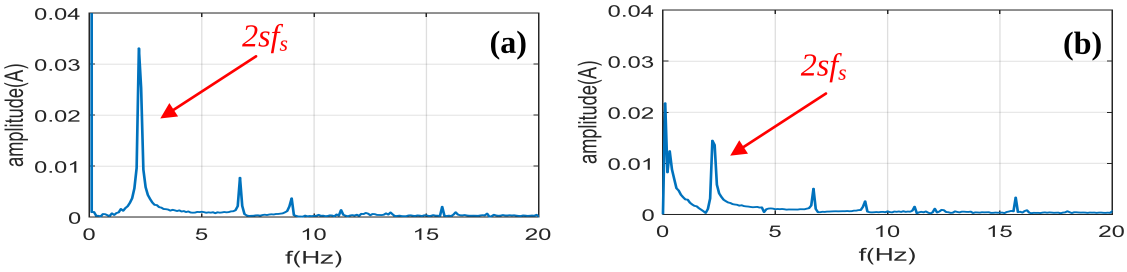

Fig. 6. Amplitude spectrum (a) and phase spectrum (b) for the case of a bar fault – Hilbert method.

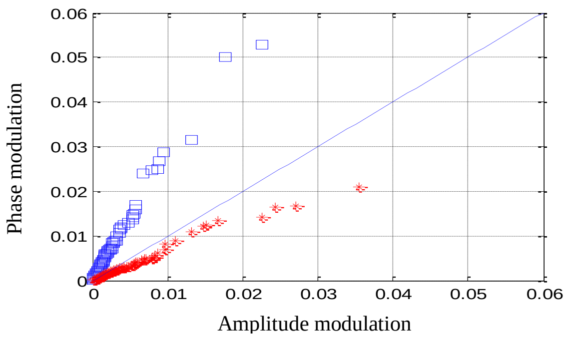

Fig. 7. Distinction between a bar fault and a load torque oscillation using the Hilbert transform method.

IV. CONCLUSIONS

This work addressed the longstanding challenge of distinguishing between broken rotor bar (BRB) faults and load torque oscillations in induction machines, particularly under low or variable load conditions where their spectral signatures overlap and compromise classical MCSA-based diagnostics. By applying Hilbert transform to the stator current, instantaneous amplitude and phase modulation signals were extracted and analyzed in the frequency domain, providing separate and meaningful diagnostic indicators. The experimental results demonstrated that BRB faults predominantly generate a strong amplitude modulation at the characteristic frequency *2sfs*, while load torque oscillations produce both amplitude and significant phase modulation at the oscillation frequency fc. The two-dimensional representation of the modulation indices further confirmed a clear clustering between the two types of disturbances, enabling reliable and intuitive discrimination. Compared to conventional MCSA, the proposed approach proved more robust and interpretable, particularly in the presence of load ripple or near-coincident fault frequencies.

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