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Reliable Detection of Broken Rotor Bars in Induction Motors via MUSIC and ZSC Methods

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Abstract – **Induction motors are used in a variety of industrial applications where frequent startups are required. In those cases, it is necessary to apply sophisticated signal processing analysis methods in order to reliably follow the time evolution of the fault-related harmonics in the signal. In this paper, the zero-sequence current (ZSC) is analysed using the high-resolution spectral method of multiple signal classification (MUSIC). The analysis of the ZSC signal has proved to have several advantages over the analysis of a single-phase current waveform. Experimentation is performed on a healthy motor, a motor with one broken rotor bar, and a motor with two broken rotor bars. The analysis results are satisfactory since the proposed methodology reliably detects the broken rotor bar fault and its severity, both during transient and steady state operation of the induction motor.**

Index Terms—**Broken bar, Fault diagnosis, Induction motor, MUSIC, ZSC**

I. INTRODUCTION

THE area of induction motor fault diagnosis has gained attention over the last two decades [1]-[3]. This is due to the keyrole played by those electrical machines in manufacturing and industrial production processes [4]. Moreover, recent works have shown that the fault detection is not always straightforward, and special cases should also be considered [5]-[8]. Furthermore, it is not enough to detect a fault but also to determine its severity with accuracy and, if possible, to predict and plan a reliable maintenance strategy [1], [4]. As a consequence, it is easy to understand that a continuous worldwide interest still exists in this challenging scientific field.

Broken rotor bars constitute about 10% of total induction motor faults [4]. The physical mechanisms, which lead to this fault, vary depending on the manufacturing type, application, and working environment, among others [4], [8]-[9]. Studies have shown that the breakage of a bar leads to overcharge of the adjacent bars, which are expected to break next [10]. However, industrial cases have shown that broken bars can exist at non-adjacent positions also [11]-[12]. Although in general, a broken rotor bar does not lead to an immediate fast catastrophic machine failure, this is not always the case. It has been shown in the past that the thermal expansion of the broken bars can lead to a damage of the stator end winding resulting in a direct heavy motor damage [13]. Furthermore, it is deduced that prompt and reliable diagnosis is a need in order to detect the fault at an incipient stage.

The literature is rich on diagnostic methods applied to the detection of broken rotor bar fault in induction motors. Vibration analysis is widely spread in industries due to the familiarization of mechanical engineers with it [10]. In the circle of electrical engineers, the most prominent method is the motor current signal analysis (MCSA), which relies on the processing of stator current with the fast Fourier transform (FFT) and a subsequent analysis of its frequency spectrum [4], [14]. Other techniques that analyses the spectra of signals like torque [15]-[16], speed [17], flux [18]-[20], and electrical power [21]-[22] are also valuable. Different signal processing techniques like the Park's vector approach [23]-[24], Hilbert transform [25], Wavelets [6]-[8], [26], Hilbert-Huang transform [27] and many others, have been applied over the years. Lately, one more signal was introduced in the field of diagnostics: the Zero-Sequence Current (ZSC). There are several advantages that make this signal very promising for real industrial applications. It is related to the saturation level of the induction motor, and this is why at no-load or low-load operation it offers very strong broken rotor bar fault related signatures whereas MCSA does not [28]. Moreover, it reveals other faults like the static eccentricity in the principal slot harmonic (PSH) of induction motors, which is not possible to observe with the analysis of a single-phase current [29]. Finally, it offers a generalized diagnosis potential as it has been shown in [30].

Usually, the analysis of the stator current relies on signal processing methods based on the FFT. These methods suffer from some known disadvantages as the spectral leakage, quantization errors and low-frequency resolution. In the case of non-stationary signals, the short-time Fourier transform (STFT) methods also have a poor time-frequency resolution that prevents the observation of low-energy harmonics close to high-energy harmonics, as the main component. High-resolution methods are necessary to overcome the drawbacks of FFT-based methods. Multiple signal classification (MUSIC) is a technique that belongs to the family of sub-space spectral estimation methods, which is particularly suited for the analysis of noisy signals [31]. It offers an excellent resolution with non-stationary signals whereas it requires only a short time window [32].

In this paper, a new methodology is proposed aiming at the reliable fault detection of broken rotor bars in induction motors under transient and steady state operation. The

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proposed method is based on the analysis of the ZSC spectrum during a start-up and a subsequent steady-state. The analysis is performed with the application of the MUSIC algorithm to extract the time-dependant behaviour of the ZSC fault-related harmonics. Experimentation is performed on a healthy motor, a motor with one broken rotor bar, and a motor with two broken rotor bars. The results prove to be satisfactory, and the fault is reliably detected as well as its severity level.

II. THEORETICAL BACKGROUND

A. The Zero-Sequence Current in Induction Motors with Broken Rotor Bars

The ZSC can be monitored in either delta-connected or star-connected, with the neutral connected, induction motors. From classical machines theory, the ZSC consists of the direct sum of the three-phase instantaneous currents:

$$i_{ZSC} = i_a + i_b + i_c \qquad (1)$$

This means that in the case of delta-connected induction motors it is required to monitor all three phase currents independently and then sum the monitored waveforms. Furthermore, in the case of star-connected induction motors one can monitor the neutral current so only one current sensor is required. If the neutral is not connected then it is evident that the zero-sequence current is zero and thus cannot be monitored for diagnosis.

Due to the stator magnetomotive forces (MMF) higher harmonic index, as well as the iron core saturation level, the fundamental harmonic of the ZSC is given by the following formula [30]:

$$I_{ZSC\_1} = 3\left[I_{ph\_3}\cos\left(3\omega_s t\right) + I_{sat\_3}\cos\left(3\omega_s t + \varphi_{sat}\right)\right] \qquad (2)$$

where:

I_{zsc_1}: fundamental ZSC harmonic
I_{ph_3}: third MMF phase current harmonic
I_{sat_3}: third phase current harmonic due to saturation
ω_s: radial supply frequency
φ_{sat}: saturation phase angle
t: time

When there is a broken bar fault, two opposite waves are created in the rotor rotating with sfs and $-sfs$, being fs the fundamental supply frequency and s the motor slip. The third stator harmonic $3fs$ induces eddy currents that produce an electromagnetic torque which induces the rotor to rotate at a speed of $3(1\text{-}s)fs$. So, the sfs and $-sfs$ travelling waves interact with the rotational speed $3(1\text{-s})fs$ and induce in the stator winding the characteristic broken rotor bar frequencies: $3fs\text{-}2sfs$ and $3fs\text{-}4sfs$. A second mechanism co-exists with the aforementioned. The $3fs$ stator rotating magnetic field induces eddy currents in the rotor with a $3sfs$ frequency. When there is present a broken bar fault, there appears another couple of opposite travelling waves with frequencies $3sfs$ and $-3sfs$. The first one is added to the $3(1\text{-}s)fs$ rotor speed and thus it rotates along to the $3fs$ stator mangetic field without inducing any broken bar fault signatures to the stator winding. However, the latter $-3sfs$ induces $3fs\text{-}6sfs$ harmonics to the stator winding. It is worth noticing that due to the speed ripple effect, harmonics at $3fs+ksfs$, k=2,4,6 are also expected, especially at greater fault-severity levels.

B. The MUSIC algorithm

The MUSIC algorithm, which was introduced at the same time in [33] and in [34], belongs to the family of methods based on the decomposition of the observation space into signal and noise subspaces. These methods have the high-resolution property. MUSIC considers that a signal *x(t)* is a sum of *P* complex sinusoids in an additive white noise:

$$x\left(t\right) = \sum_{k=1}^{P} A_k e^{j\left(2\pi f_k t + \varphi_k\right)} + w\left(t\right) \qquad (3)$$

where A_k is the amplitude, f_k is the frequency, φ_k is the phase of the k_{th} space vector and *w(t)* is white noise, and *P* is also known as the MUSIC order. The sinusoid amplitude and frequency are not random and unknown. The phases of the sinusoids are uncorrelated random variables, uniformly distributed over the interval $[-\pi, \pi]$.

The power spectrum of *x(t)* consists of a set of *P* impulses of area $2\pi|A_k|$ at frequencies f_k for $k = 1, 2, ..., P$, plus the power spectrum of the additive noise *w(t)*. Based on the orthogonality of the signal and noise subspaces, the MUSIC pseudo-spectrum P_{MUSIC} of the current space vector is given by the following frequency estimation function:

$$P_{MUSIC}\left(f\right) = \frac{1}{\sum_{i=P+1}^{M}\left|\bar{e}_i^{H}\bar{v}_i\right|^2} \qquad (4)$$

where $\bar{v}_i$ is the noise eigenvector and $\bar{e}_i^{H}$ is the signal vector defined as $\bar{e}_i^{H}\left(f_i\right) = [1, e^{-j2\pi f_i}, \ldots, e^{-j2\pi f_i(M-1)}]$. The Eq. 4 shows a maximum when, for a certain f_k truly present in the signal, the signal and noise subspaces projections are zero.

III. EXPERIMENTS

Experimental tests are carried out using a 1.1 kW, 4-pole induction motor. Table I shows the rated characteristics of this motor. The motor is coupled to a DC machine that acted as the mechanical load. The different load levels are obtained by varying the excitation current of the DC machine. The supply voltage of the tested motor could be easily changed with the aid of an autotransformer. Fig. 1 (a) shows a picture of the test bench.

TABLE I
INDUCTION MOTOR CHARACTERISTICS

Rated Power	1.1 kW
Rated frequency	50 Hz
Rated Voltage	230 V
Rated primary current	4.5 A
Rated speed	1410 rpm
Rated slip	0.06
Stator windings connection	Delta
Number of pole pairs	2
Number of rotor bars	28
Number of stator slots	36

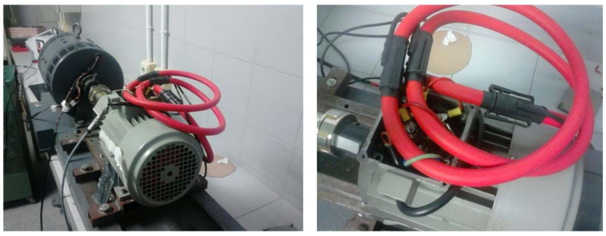
(a) (b)

Fig. 1. Experimental test bench: a) motor-load bench and b) the current clamps configuration.

Three different motor conditions are tested: healthy state, motor with one broken rotor bar and motor with two adjacent broken rotor bars. The bar breakages were forced by drilling holes in the corresponding bars at their junction point with the short-circuit end-ring. Each drilling was carried out in such a way that the complete breakage of the corresponding bar is guaranteed. Different motor startups are carried out at different voltage-supply levels.

In each test, the three phase currents are acquired during the motor startup by using current clamps, connected to a waveform recorder (YOKOGAWA DL-850). Fig. 1 (b) shows a detail of the current clamps. The signals are captured at a sampling rate of 5 kHz and the register length is 100 seconds, which guarantees the acquisition of all the startup as well as a significant portion of the steady-state regime. The current signals are initially stored in the recorder and afterwards transferred to a computer, where the *ZSC* is computed and further analyzed.

IV. RESULTS

In this section, the analysis results are presented. Nine currents, that contain an initial start-up and the subsequent steady-state, have been analyzed. The ZSC is calculated from the three phase currents of the motor, acquired in each test. The ZSC is preprocessed by resampling to a final 1024 Hz sampling frequency and then filtered through a low-pass filter with a cut-off frequency of 200 Hz. Afterwards, the pseudospectrum is estimated using MUSIC.

MUSIC provides a spectrogram of the ZSC for every measured induction motor case. So, Figs. 2 to 10 depict the spectrograms of the nine ZSC cases. The MUSIC order used to analyze each ZSC is indicated in the figure label. This parameter is determined experimentally for each analyzed signal. The window length is the same for all cases and it is set to 0.20 s. A window overlap of one sample is used in all cases.

Figs. 2-4 represent the results of the three condition cases with the motor operating at no load. The analysis of the healthy motor spectrogram (Fig. 2) offers some interesting characteristics. Firstly, the fundamental ZSC current harmonic at 150 Hz is very clear. At the same time, the fundamental phase current harmonic at 50 Hz, due to some level of 3-phase supply unbalance, is also strong. The supply imbalance is also verified by the existence of an important 2*sfs* component at 100 Hz. The inherent mixed-eccentricity harmonic close to 25 Hz is also present. Finally, a V-shape is observed at 150 Hz and it drops to 50 Hz. In Fig. 4, it is shown the spectrogram of the motor at no-load and with two broken bars. If it is compared with the healthy case (see Fig. 2), it is observed supplementary information. A second V-shape appears at 150 Hz and it drops to 0 Hz. The energy close to the ZSC fundamental seems increased because the broken bar fault signatures are located very close to the 150 Hz. Interestingly, in the case of the two broken bars (Fig. 4), the inherent mixed-eccentricity harmonic close to 125 Hz appears. Moreover, Fig. 3 illustrates the spectrogram of the motor with a broken rotor bar and operating at no load. It is anticipated the results observed in the case of 2 broken rotor bars (Fig. 4), but with a lower energy level. Even at no load, the energy of the fault related harmonics increase during the transient start-up.

The MUSIC spectrograms of the cases where the motor is at half-load are exhibited in Figs 5-7. The healthy motor shows a behavior very similar to the no load case (Fig. 5).

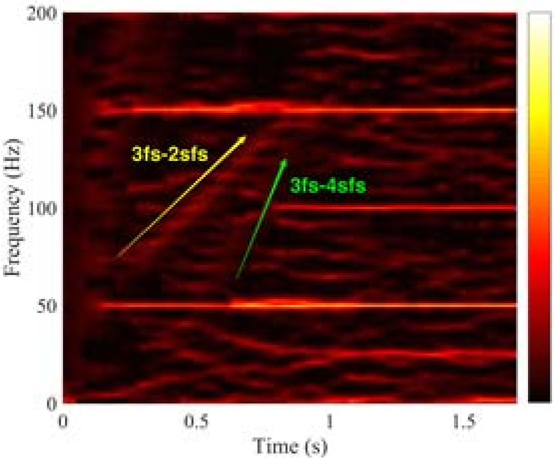

Fig. 2. MUSIC (order 36) spectrogram of the motor in healthy condition and at no load.

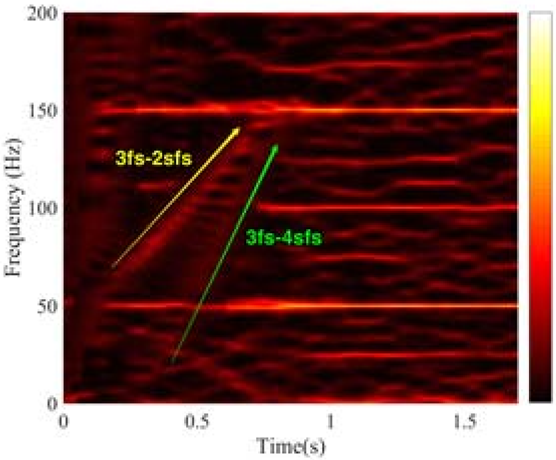

Fig. 3. MUSIC (order 40) spectrogram of the motor with 1 broken rotor bar and at no load.

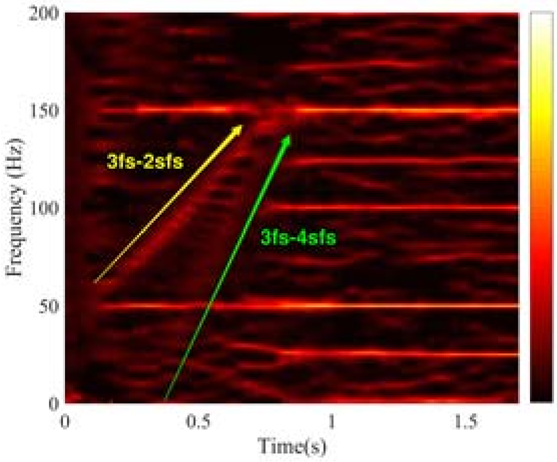

Fig. 4. MUSIC (order 39) spectrogram of the motor with 2 broken rotor bars and at no load.

The MUSIC spectrogram of the motor with 1 broken rotor bar (see Fig. 6) shows a second V-shape trajectory, while the 3*fs*-2*sfs* and 3*fs*-4*sfs* sidebands are clearly visible and with a high-energy amplitude. Fig. 7 shows the MUSIC spectrogram of the induction motor case with 2 broken rotor bars. A second V-shape trajectory can be recognized and the ZSC sidebands around the 150 Hz are identified with high energy, as in the case of one broken bar. Additionally, the inherent mixed-eccentricity harmonic close to 125Hz increases. Finally, the left sideband of the inherent mixed-eccentricity harmonic close to 25 Hz also increases.

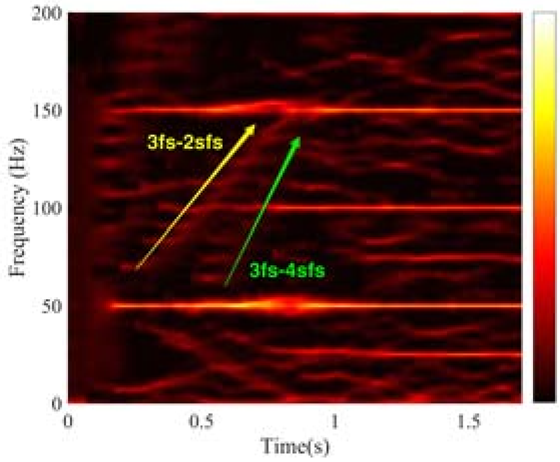

Fig. 5. MUSIC (order 38) spectrogram of the motor in healthy condition and at half load.

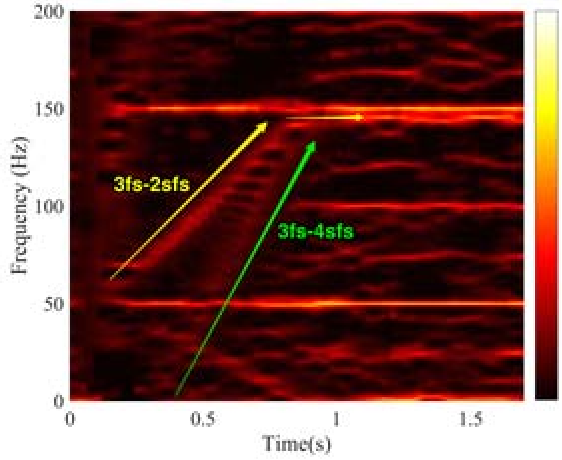

Fig. 6. MUSIC (order 38) spectrogram of the motor with 1 broken rotor bar and at half load.

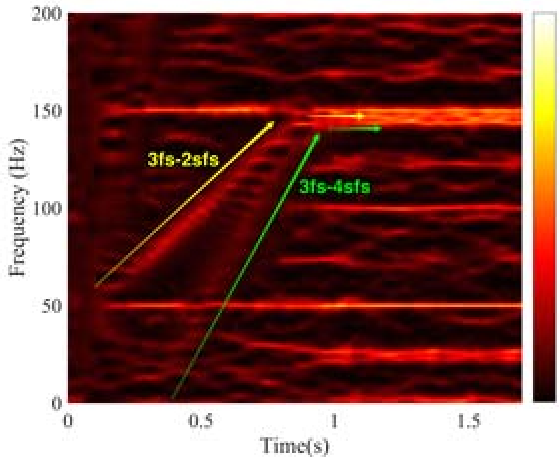

Fig. 7. MUSIC (order 44) spectrogram of the motor with 2 broken rotor bars and at half load.

Finally, the results of motor operating at full load are shown in Figs 8-10. At full load, the healthy motor displays two V-shape trajectories in the MUSIC spectrogram (see Fig. 8). Yet, none of them drops to 0 Hz. The ZSC sidebands are visible, possibly because of inherent rotor asymmetries and shaft-load misalignment. The left sideband of the inherent mixed-eccentricity harmonic close to 25 Hz can also be observed, but this may be related to the aforementioned asymmetries and not the broken bar fault. In both faulty cases, the second V-shape trajectory drops to 0 Hz (see Fig. 9 and 10). It is also noticeable in Fig. 9 for 1 broken rotor bar that the 3*fs*-6*sfs* band appears.

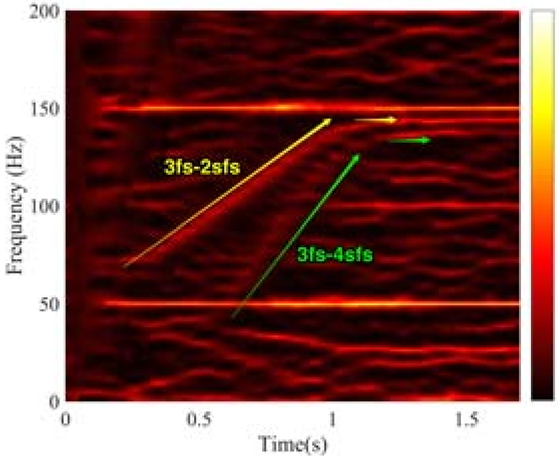

Fig. 8. MUSIC (order 42) spectrogram of the healthy motor and at full load.

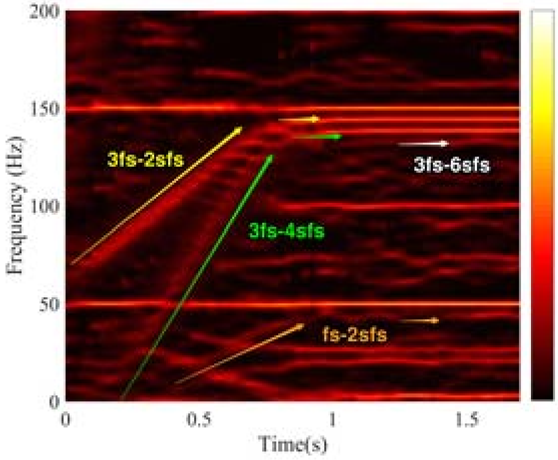

Fig. 9. MUSIC (order 38) spectrogram of the motor with 1 broken rotor bar and at full load.

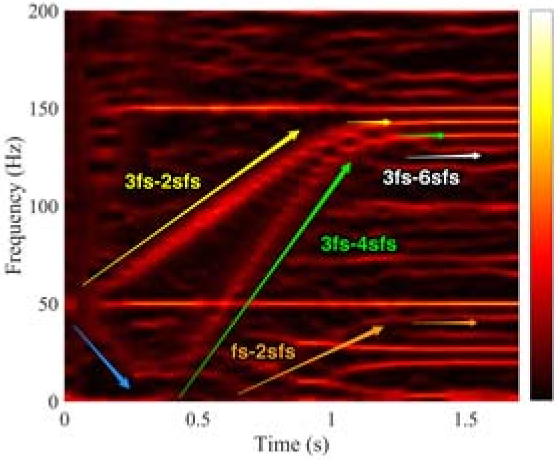

Fig. 10. MUSIC (order 42) spectrogram of the motor with 2 broken rotor bars and at full load.

The MUSIC spectrogram displays excellent diagnostic capabilities when the motor with 2 broken rotor bars is at full load (see Fig. 10). Besides, in the above-mentioned signatures, it is increased the energy of the left sideband harmonic around the 125 Hz inherent mixed-eccentricity harmonic. Also, the right sideband harmonic close to 75 Hz, due to inherent mixed-eccentricity, is also visible, as well as the left sideband at 50 Hz. Finally, both sidebands of the inherent mixed-eccentricity harmonic close to 25 Hz are easily noticed.

The MUSIC spectrograms permitted to identify some fault-related signatures unequivocally in the time-frequency plane during the start-up transient and the following state-state (see Fig. 10). Two trajectories are born at 50 Hz and evolve to the 150 Hz harmonic. These patterns correspond to the 3*fs*-2*sfs* and 3*fs*-4*sfs* sidebands, which display a higher energy as the fault severity increases. The first sideband goes straight from 50 to 150 Hz. The second sideband depicts a trajectory with a V-shape pattern. A third sideband, 3*fs*-6*sfs*, appears at steady state in the case of two broken rotor bars. It is also present the lower side band *fs*-2*sfs*, observable in the phase-current spectrum during the startup of line-fed IM with a rotor asymmetry.

V. CONCLUSIONS

In this paper, a novel methodology for the diagnosis of broken rotor bars is presented. The proposed method is based on a high-resolution spectral analysis of the zero sequence current with a multiple signal classification technique. This methodology has been tested experimentally in a controlled laboratory experiment. A line-fed induction motor has been tested at different loads and in three condition states: healthy, with one broken rotor bar and with two broken rotor bars.

The ZSC, computed from the three phase currents during the startup, is analyzed with MUSIC, which provides a high spectral resolution during the motor transient and the subsequent steady state as well. This signal, compared to the phase current usually utilized for monitoring purposes, has demonstrated to be very sensitive to the motor condition, even when the motor is at no load or very low load levels.

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