Asymmetrical Fault Detection in Induction Motors through Elimination of Load Torque Oscillations Effects in the Slight Speed Variations and Steady-state Conditions

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***Abstract*— Recently, motor current signature analysis (MCSA) has been widely considered for fault detections due to its simplicity, availability, and cost-effectiveness. The rotor asymmetry fault (RAF) is the most common fault that occurs in induction machines. It is extremely challenging to detect RAF indices occurred at the vicinity of the supply frequency. Moreover, load torque oscillations (LTOs) which appear as a sinusoidal phase modulation of the supply frequency, exhibit similar indications as the RAF, especially in gearbox-based electromechanical systems. Since LTOs lead to false alarm of RAF, separation of LTOs indices from RAF characteristic components is inevitable. In this paper, normalized frequency domain energy operator (NFDEO) is evaluated for demodulation and separation of RAF and LTOs in steady-state and transient conditions. Moreover, the proposed method is tested in both with-and-without speed control strategies. In this regard, the effects of RAF in the presence of LTOs investigated through both synthetic signals and experimental data in steady-state and transient conditions with slight variation in rotor speed. The obtained results show that NFDEO along with Winger-Ville can effectively detect RAF in the presence of LTOs even with speed control strategy.**

***Index Terms*—Induction motor, Fault detection, Condition monitoring, Fault diagnosis, Spectrum analysis.**

NOMENCLATURE

i_N	Stator current in a healthy IM
I_s	Maximum stator current amplitude
f_s	Supply frequency
f_{af}	Asymmetric fault characteristic frequency
s	Slip
β	Modulation index of asymmetric fault
n_f	Number of BRBs
N_b	Number of rotor bars of the studied IM
i_{AF}	Stator current of an IM with asymmetric fault
f_{LTO}	Load torque oscillation frequency in torque of machine
f_{s_LTO}	Load torque oscillation frequency in the stator current signature
Gp	Gear ratio
T_{Ld}	Load torque
T_e	Electro-mechanical torque
T_{Lo}	Load torque oscillation component's
f_{LTO}	Load torque oscillation frequency
i_{s_LTO}	Stator current of IM including effects of LTOs
J_n	n^{th} order of Bessel function
γ	modulation index of LTOs
$i_{s\_AF\_LTO}$	stator current of a faulty IM
I_r	rotor current of an IM
$\Psi[y(t)]$	TKEO of y(t)
$Env\ [y(t)]$	squared envelope of y(t)
$\tilde{y}(t)$	Hilbert transform of y(t)
$\dot{y}(t)$	derivative of y(t)
$Env_N[x(t)]$	normalized energy operator

I. INTRODUCTION

INDUCTION machines (IMs) are used in a wide variety of industrial applications such as automobiles, traction systems, wind turbines, agriculture and so on. A specific type of these motors is wound rotor induction motors (WRIM) which provides high starting torque by connecting an external resistance to the rotor circuit. Conveyors, cranes, compressors, and elevators are some applications that use WRIM. Condition monitoring is often desired to decrease huge economical losses and increase the reliability, productivity, and safety [1].

Several strategies have been used for the detection of mechanical and electrical faults in electrical machines in recent years such as acoustic emission analysis [2], acoustic signature analysis [3-4], flux-based detection [5-39], air gap analysis [40] vibration signature analysis [6], thermal analysis [7-8], neural networks [9], motor current signature analysis [10-12], etc. The motor current signature analysis (MCSA) method can be mentioned as one of the simple and cost-effective strategies [13-15]. In general, low-cost nature of current signal measurement, made MCSA-based condition monitoring very attractive. In one of the relevant previous works, the authors have analyzed active and reactive current signals, which has an ability to separate rotor asymmetry fault (RAF) from load torque oscillations (LTOs) in steady-state conditions [16]. However, this method requires measurement of three-phase current. In addition, no transient analysis has been reported in this work. In another approach, analyzing the positive and negative sequences of the three-phase motor current signals is used to eliminate the false indications of broken rotor bar (BRB) from LTOs [17]. This method also requires three-phase current measurement. Another study has been performed based on the analysis of Clark transformation for motor current, which can isolate BRB' fault from the LTOs [18]. In this method, the Park transformation is employed after collecting the current and voltage signals of three phases. Then, the q-axis of stator current and stator voltage (i_q, v_q) are used to detect the asymmetric fault characteristic frequency components. Finally, by comparing the two fault indices against the q-axis component, the faults can be detected. By using rectified stator current, the fault indices can also be demodulated from the main signal in the steady-state conditions [19]. The Teager-Kaiser energy operator (TKEO) has also been reviewed and analyzed which requires causal processing leading to phase distortion [20]. The data collected from the motor (current signal) can be analyzed and processed by a wide range of signal processing methods to extract specific features of fault. A method including zero sequence current analysis (ZSC) under transient operation in the motor is proposed in [21]. In this method, the fault is detected in induction motor by short-time Fourier transform. In another work, the motor current signature analysis in transient conditions for an induction motor, powered by a voltage source inverter (VSI), is presented [22].

In [23], Kaiser introduced a simple algorithm to calculate energy of a signal and formulized an *energy operator*. Later, Teager used this approach for speech analysis. Energy operators have been considered in recent years for fault detection in electric motors. One of these energy operators is the Teager-Kaiser Energy Operator (TKEO). When the modulation component changes slowly, it was found that the TKEO is approximately equal to the squared envelope of the derivative of a signal [24]. Phase distortion and non-ideal filter characteristics are some important disadvantages of TKEO. Frequency domain energy operator (FDEO) is another technique which does not require causal processing. The benefits of FDEO for faults detection, such as in gear and bearing faults, have already been validated [25]. This energy operator not only has the ability to demodulate the signal by an ideal filter in the frequency spectrum (one-way), but it can also exactly differentiate the signal by multiplying it by $j\omega$ on the same frequency band [25]. In other words, normalized FDEO (NFDEO) eliminates the effects of main component frequency (supply frequency) which improves the detectability of fault characteristic frequency [26].

The fault frequency of load torque oscillation is usually very close to the RAF. On the other hand, the RAF is close to the supply frequency, so it is difficult to distinguish these two fault frequencies from the main frequency. The core idea in our study is to use NFDEO as a pre-processing method along with Wigner-ville distribution to isolate and demodulate the harmonic spectrum caused by RAF and LTOs. In the proposed approach, only one phase of the induction motor current needs to be processed, and there is no need to involve the three-phase current in the fault detection process. This means less complexity and storage requirements. In the proposed method, NFDEO is applied to the raw collected current signal as a preprocessing stage. NFDEO provides a clear distinction between the amplitude and phase part of the current signal. After this stage, the asymmetric fault can be detected from the LTOs by using FFT (steady-state condition) and Wigner-ville distribution (transient condition). The proposed strategy provides reliable separation technique for RAF from stator current in transient conditions. To validate this approach, a WRIM has been tested. Furthermore, most of the existing works examined only the starting moments of the induction motor, and the effect of slight slip changes during operation was not considered for transient analysis. Hence, in this paper we perform the transient condition analysis through applying small slip changes during motor operation.

In order to improve the performance of the previous time-frequency methods such as STFT, the Wigner distribution has been investigated by researchers, which provides the spectral density of the signal as a function of time. STFT supplies specified time-frequency resolution because of fixed length window function. WVD eliminates this resolution problem, but cross terms (interference) are present. Pseudo WVD eliminates these cross terms by using smoothening window function applied to WVD either in the time or frequency domain. PWVD has been used in literature for different applications such as gear fault diagnosis [38]. Therefore, in this paper the combination of PWVD technique with NFDEO is used for detection of fault in the current signature of machine. Our method is compared with TKEO technique in transient and steady-state conditions.

The rest of this paper is organized as follows: Section II examines the mathematical models of the stator current under normal and fault conditions. In Section III, mathematical and theoretical definitions of the proposed method are presented. Section IV presents the results for experimental and synthetic signal to validate the proposed method. Finally, the conclusions are presented in Section V.

II. Mathematical Models of Currents and Faults in Induction Motors

A. Asymmetric Fault

A simplified description of one phase stator current ($i_N(t)$) can be written as follows:

$$i_N(t) = I_s \cos(2\pi f_s t) \tag{1}$$

In IMs with asymmetric faults, periodical disturbances generated by the fault, lead to the amplitude modulation of stator current. In this case, the inverse-sequence of $-sf_s$ arises which leads to fault characteristic frequency at $(1\text{-}2s)f_s$ in the spectrum of stator current signature. The asymmetry fault characteristic component in turn leads to electromagnetic and mechanical interactions as follows [41]:

$$f_{af} = 2\zeta s f_s, \zeta = 1, 2, 3, ... \tag{2}$$

which ζ shows the harmonics and s is the slip of machine. In most cases, ζ is considered 1, because the first harmonic is the dominant frequency used for fault detection process. By using the fault characteristic component and its harmonics mentioned in (2), the synthetic signal of the stator current with considering asymmetry fault ($i_{AF}(t)$) can be written as:

$$i_{AF}(t) = I_s \cos(2\pi f_s t)(1 + \beta \cos(2\pi f_{af} t)) \tag{3}$$

Generally, β can be introduced for BRB fault via the following equation:

$$\beta \approx \frac{n_F}{N_b} \tag{4}$$

Considering the first harmonic of fault components (ζ=1) and the existing trigonometric equation, the stator current with asymmetry fault can be expressed by:

$$\begin{aligned} & i_{AF}(t) = I_s \cos(2\pi f_s t) + \\ & \frac{\beta}{2}[I_s \cos(2\pi f_s (1-2s)t + I_s \cos(2\pi f_s (1+2s)t] \end{aligned} \tag{5}$$

Some usage of the induction motor causes a small slip such as inverted-fed induction motors [27] and small motors working under low load conditions [28]. The main challenge occurs when the slip is very small because the fault index will get close to the supply frequency.

B. Load torque oscillations

LTOs occur under load anomalies conditions such as abnormal mechanical conditions and gearbox failure (6). The generated LTOs emerge as additive frequency around the supply frequency in the stator current signature of IMs (7) [17, 36]. It can be observed from (7) that these sideband frequencies approach to the supply frequency in the presence of gearbox with the gear ratio of G_p from two sides.

$$T_{Ld}(t) = T_e + T_{LO}\cos(2\pi f_{LTO}t) \tag{6}$$

$$f_{s\_LTO} = f_s \pm kf_{LTO} = f_s \pm k(1-s)f_s / G_p \tag{7}$$

The effect of LTOs on the motor current leads to phase modulation (PM). Finally, a phase modulation is emerged in the stator current, where the frequency of this modulation is given by (7). According to this phenomenon, the motor current can be written as follows:

$$\begin{aligned} i_{s\_LTO}(t) &= I_s\cos(2\pi f_s t + \varphi) + \\ &+ I_s J_1(\gamma)\cos(2\pi(f_s + f_{LTO})t) + \\ &+ I_s J_{-1}(\gamma)\cos(2\pi(f_s - f_{LTO})t) \end{aligned} \tag{8}$$

Finally, by combining (5) and (8), the synthetic signal of stator current ($i_{s\_AF\_LTO}$), which covers both RAF and LTOs, can be obtained as (9).

$$\begin{aligned} & i_{AF}(t) = I_s\cos(2\pi f_s t) + \\ & \frac{\beta}{2}[I_s\cos(2\pi f_s(1-2s)t + I_s\cos(2\pi f_s(1+2s)t] + \\ & I_r\cos(\omega_s t + \gamma\sin(2\pi f_{LTO}t)) \end{aligned} \tag{9}$$

III. Proposed Fault Diagnosis Approach

A. Teager-Kaiser Energy Operator

Initially, Teager introduced the concept of energy operator, and its performance was later improved by Kaiser, for speech analysis applications [29-30]. The Teager-Kaiser Energy Operator (TKEO) has been studied and used for machinery fault diagnosis such as gearbox and bearing [31-32]. It was found that TKEO is approximately equal to the squared envelope of the derivative of a signal when the modulation component changes slowly. The mathematical equation of TKEO for continuous and discrete signals (ψ_c, ψ_d) are expressed via (10) and (11), respectively:

$$\psi_c(y(t)) = [\dot{y}(t)]^2 - y(t)\ddot{y}(t) \tag{10}$$

$$\psi_d(y[n]) = (y[n])^2 - y[n+1]y[n-1] \tag{11}$$

By considering $y(t) = A(t)\cos(\phi(t))$, the following equations can be obtained:

$$\begin{aligned} y(t) &= -\dot{\phi}(t)A(t)\sin\phi(t) + \dot{A}(t)\cos\phi(t) \\ &\approx -\omega(t)A(t)\sin\phi(t) \end{aligned} \tag{12}$$

$$\begin{aligned} \ddot{y}(t) &\approx -\dot{\omega}(t)A(t)\sin\phi(t) \pm \dot{A}(t)\omega(t)\sin\phi(t) \\ &- \omega(t)A(t)\dot{\phi}(t)\cos\phi(t) \approx [\omega(t)]^2 A(t)\cos\phi(t) \end{aligned} \tag{13}$$

where $\omega(t) = \dot{\phi}(t)$. Due to slowly varying frequency and amplitude relative to time, the derivative of A ($\dot{A}(t)$) and ω ($\dot{\omega}(t)$) can be ignored($\dot{A} = \dot{\omega} = 0$). Thus, TKEO of y(t) would be equal to:

$$\begin{aligned} & \psi_c[y(t)] = [\dot{y}(t)]^2 - y(t)\ddot{y}(t) \\ & \approx [\omega(t)]^2[A(t)]^2(\sin^2\phi(t) + \cos^2\phi(t)) \\ & = [\omega(t)]^2[A(t)]^2 \end{aligned} \tag{14}$$

B. Normalize Frequency Domain Energy Operator

Frequency domain energy operator (FDEO) is also used in this context. Signals can be analyzed in the frequency domain by FDEO. This energy operator is proposed by Randall and Smith in [25]. TKEO has phase distortion because it requires casual processing. In contrast, FDEO is calculated by the Hilbert transform and does not require causal processing, hence, phase distortion is avoided. The effectiveness of the frequency domain energy operator for RAF detection have been reported in [25].

Based on [25, 26], the energy operator can be estimated by the sum of the squares of the signal and its corresponding Hilbert transform. Assuming the current signal denoted by y(t), then:

$$Env[y(t)] = y(t) + \tilde{y}(t) \tag{15}$$

The square of $\dot{y}(t)$ is obtained from the following equation.

$$Env[\dot{y}(t)] \sim [-\omega(t)A(t)]^2 \tag{16}$$

Considering (14) and (16), the following expression for FDEO can be obtained.

$$\psi[y(t)] \approx Env[\dot{y}(t)] \tag{17}$$

$$\begin{cases} A = \sqrt{Env[y(t)]} \\ \omega = \sqrt{\dfrac{Env[\dot{y}(t)]}{Env[y(t)]}} \end{cases} \tag{18}$$

Finally, by normalizing this energy operator, normalized FDEO (Env_N) can be written as follow [26]:

$$Env_N[y(t)] = \frac{Env[y(t)] - \overline{Env[y(t)]}}{\overline{Env[y(t)]}} \tag{19}$$

After estimating the amplitude and phase signals (A, ω), it is possible to observe the asymmetric fault index and load torque oscillation by simple spectrum analyze in steady-state condition. To see the fault index in transient condition, after calculating these two signals (A, ω), advanced signal processing method need to be used.

C. Description of the Wigner-ville Distribution Method

Since the frequency of the fault index changes due to variation in the slip of machine, the faulty signal is considered to be non-stationery, and it requires time-frequency analysis. Moreover, RAF characteristic frequency in the experimental results need a time-frequency method with high-resolution capability especially in transient conditions. One possible method for signal processing in the time-frequency domain is the Wigner-ville distribution (WVD).

Eugene Wigner proposed Wigner distribution in 1932 and its importance in quantum mechanics and fuzzy space has been proven in [33]. In order to process a signal in the time-frequency domain, several methods can be used, such as short-time Fourier, Gabor, wavelet, etc. [34]. By comparing the Wigner distribution with other transformations, we found that the WVD has a relatively high resolution in frequency domain and thus suitable in fault diagnosis process. WVD can be expanded by the following equations:

$$\begin{aligned} WVD_x(t,\omega) &= \int_{-\infty}^{\infty} x\left(t + \frac{\tau}{2}\right)x^*\left(t - \frac{\tau}{2}\right)e^{-j\omega\tau}d\tau \\ &= \int_{-\infty}^{\infty} g_x(t,\tau)e^{-j\omega\tau}d\tau \end{aligned} \tag{20}$$

where x^* is a complex conjugate of x. Finally, WVD can be rewritten as below.

$$WVD_x(t,\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X\left(\omega+\frac{\varphi}{2}\right)X^*\left(\omega-\frac{\varphi}{2}\right)e^{jt\varphi}d\varphi = \frac{1}{2\pi}\int_{-\infty}^{\infty} \chi_x(\omega,\varphi)e^{jt\varphi}d\varphi \quad (21)$$

In practice, a smoother version of WVD, called the Pseudo Wigner-ville (PWD), is often used, which is obtained from the following equation.

$$PWD_x(t,\omega) = \int_{-\infty}^{+\infty} p(\tau)x\left(t+\frac{\tau}{2}\right)x\left(t-\frac{\tau}{2}\right)e^{-j\omega\tau}d\tau \quad (22)$$

where $p(\tau)$ is the smoothing window for WVD which reduces the amplitudes of the interference terms. Since the window is a function of τ, the smoothing occurs in the frequency domain only. Therefore, this type of smoothing does not undermine time resolution.

D. Proposed configuration

The main goal in this paper is to separate the asymmetry fault characteristic in the presence of LTOs in order to avoid false alarm of asymmetry fault. In addition, we are interested in demodulating faulty signal from the supply frequency with less current sensors. Since LTOs and rotor asymmetry faults lead to phase modulation and amplitude modulation of stator current of IMs, respectively, we aim to separate phase and amplitude signals to identify faults. To do this, NFDEO is used in this paper, which only requires one phase of the motor current data. After separating the amplitude signal, which is related to the asymmetry motor fault, the fast Fourier transform (FFT) can be used to observe the fault index in a steady-state condition. However, in the transient condition, the NFDEO method must be used along with the WVD to observe the time-frequency spectrum and detect asymmetry fault. The main steps of the proposed approach are briefly presented in Fig. 1.

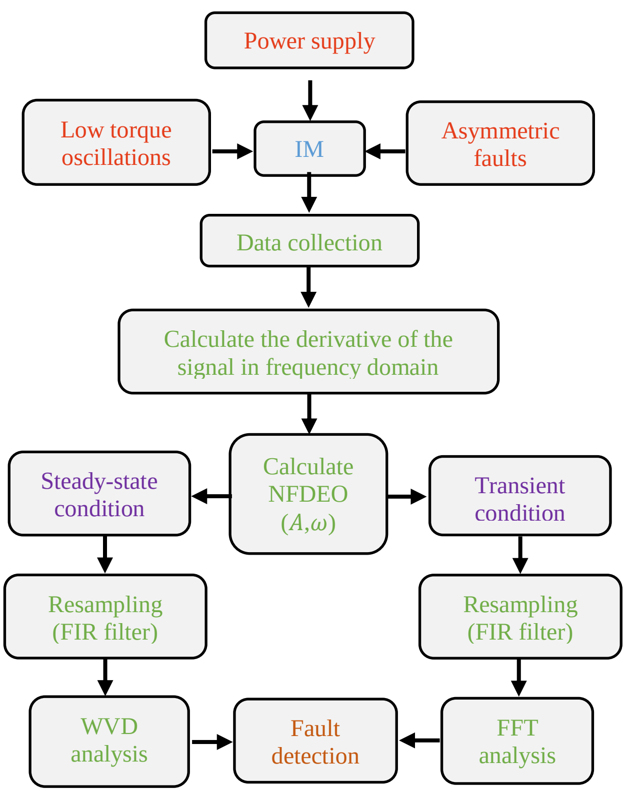

Fig. 1. Flow chart of the proposed method

(1) Motor starts working with unbalance fault and load torque oscillation as shown in the Fig.1.
(2) After the acquisition of the IM stator current, the derivative of current signal should be calculated for envelope analysis.
(3) For pre-processing, NFDEO is applied to the collected signals to obtain two signals (A, ω).
(4) Finite impulse response (FIR) filter is used after calculated NFDEO to achieve high resolution output results.
(5) Finally, the state of the motor should be checked for steady-state and transient analysis.

In fact, the purpose of this paper is to separate the RAF index from the LTOs in the stator current signature of IMs. Since the RAF and LTOs affect on the amplitude and the phase of the current signal, respectively, this study focuses on separating the amplitude and phase of the current signal. For this purpose, the NFDEO method has been considered due to its relative advantage over the previous TKEO method. The obtained amplitude and phase are analyzed to detect the RAF and LTOs indices, respectively.

IV. Results

4.1 Analytical Results

The analytical signal obtained in (9) has been used to generate synthetic signals in MATLAB environment (Fig. 2.a). To validate the proposed method, the signal processing is performed in both steady-state and transient conditions. The parameters of the synthetic signal can be seen in Table 1.

TABLE I
SPECIFICATION OF SYNTHETIC SIGNAL

Parameter	value
β	0.05
I_s (A)	1
I_r (A)	1
f_s (Hz)	50
f_{LTO} (Hz)	2.5
γ	0.03

For the steady-state case, slip and LTOs frequency are consider constant ($S = 0.02$, $f_{LTO} = 2.5\ Hz$). It is necessary to note that the asymmetry fault component and LTOs have been adjusted close together to verify the effectiveness of the proposed approach in isolation of rotor asymmetry fault characteristic from LTOs. In transient case, slight variation in the slip of machine has been investigated. In this case, the motor starts operating at slip equal to 0.015, which is then gradually increased to 0.025 at the fifth second.

In this case, the LTOs are kept almost constant with considering the mathematical equations related to IMs, so that their effects can be observed after processing the analytical data in the transient mode.

A. steady-state condition

Fig. 2a shows an analytical signal at a sampling frequency of 5 kHz for 12 seconds according to (9). In this signal, asymmetry fault and LTOs are also applied. Fig.2c shows the demodulated signal with the frequency related to the asymmetry fault frequency in the steady-state condition. Considering the s = 0.02, the main component of the asymmetry fault frequency can be observed in Fig.2b at the frequency of 2 Hz. In Fig.2f, the frequency of LTOs is well distinguishable from the asymmetry fault frequency by using the proposed method. Finally, as the results show, the proposed method has been able to separate the two asymmetry faults and LTOs, effectively.

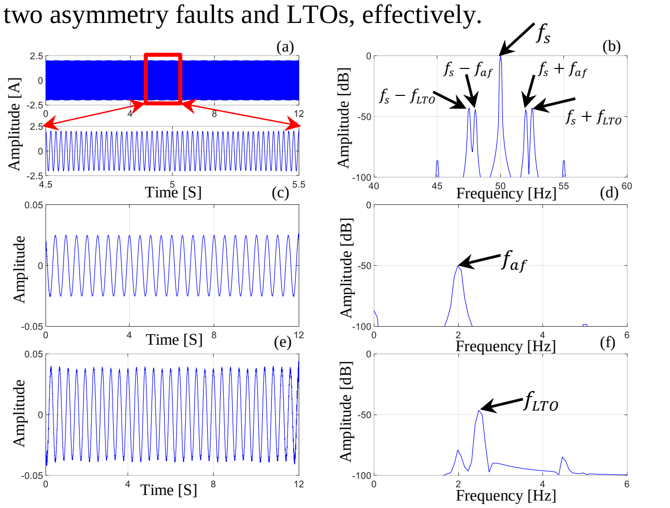

Fig. 2. Spectral analysis of proposed method using analytical faulty stator current with sampling frequency of 5kHz for steady state condition and (s = 0.02) a) Stator current waveform under fault conditions. b) Fourier transform of current signal. c) Demodulation signal (amplitude) for asymmetry fault. d) Fourier transform of the amplitude signal. e) Demodulation signal (phase) for LTO. f) Fourier transform of the phase signal.

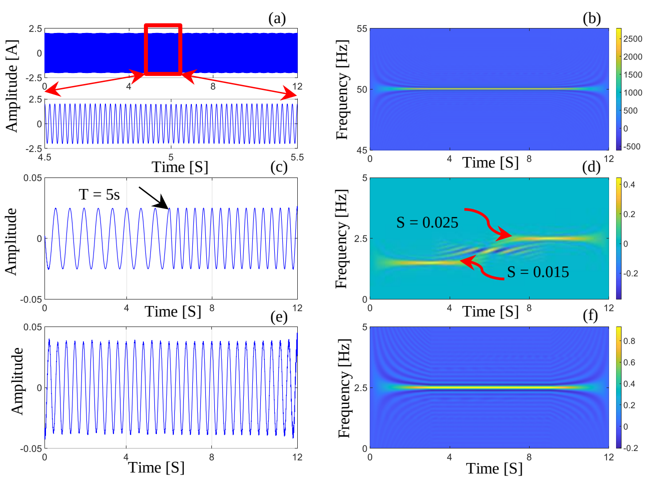

Fig. 3. a) Stator current signal in transient condition despite asymmetry fault and LTOs. b) WVD for stator current signal in transient condition. c) Demodulation signal (amplitude) for asymmetry fault. d) WVD for amplitude signal. e) Phase signal. f) WVD for phase signal.

B. Transient condition

The specifications of the signal used in transient condition are similar to that used for steady-state condition except for slip value. Slip changes from 0.015 to 0.025, which is clearly visible in Fig.3c. This issue has been carried out to observe the effectiveness of the proposed method in the transient condition. Although slip changes are occurred in the fifth second, and the slip of the machine is increased, the frequency of LTOs kept approximately constant, which can be observed in Fig.3e. We used the Pseudo WVD (PWVD) distribution to detect the fault index with high resolution in time-frequency domain. Fig.3b shows the PWVD of the original signal in which the asymmetry fault cannot be detected. After pre-processing the main signal (i.e., applying NFDEO) and obtaining the amplitude and phase signals to detect and separate the fault index, the PWVD can be used to extract the fault index in the transient condition (Fig. 3b).

4.2 Experimental Results

In this section, the laboratory and test-rig setup are first described to obtain stator current data. Then, the stator current data is used for asymmetric fault diagnosis in steady-state and transient conditions in IM. Thus, the performance and effectiveness of the proposed approach are introduced. At last, a critical comparison with other strategies such as TKEO demonstrated the advantages of the presented approach.

A. Test-rigs description

In order to validate the effectiveness of proposed method, a WRIM, shown in Fig.4 is tested. The test was performed in both steady-state and transient conditions. The analysis of faults in the steady-state conditions is evaluated in two cases: motor with speed control and motor without speed control. Some methods, such as the method in [17], use positive and negative sequences of current signals. In these cases, the side bands of faults need to be equal approximately. This is not the case when the speed of IMs is controlled. In squirrel cage induction motors, asymmetry fault in the rotor usually occurs due to the broken rotor bars or the end rings. Nevertheless, in WRIM, when the rotor coils are short circuit together, the resistance of one phase increases and an asymmetry occurs between the resistors of the three phases. However, to model this type of fault in the laboratory, an external resistor is applied to the motor windings of one phase.

For each test in steady-state condition, 25k samples were used at a sampling frequency of 2 kHz, and for the transient condition, 32k samples were used at a sampling frequency of 2.5 kHz. The fundamental frequency of the used WRIM is 50 Hz, and according to the Nyquist theorem, the sampling frequency should be at least 100 Hz. However, the sampling frequency should be 10 - 20 times the Nyquist standard in real applications [37]. Rotor speed for steady-state condition with control is equal to 1450 rpm and without control is equal to 1470 rpm. For transient condition, the motor speed varies between 1400 and 1450 rpm. Finally, the specifications of WRIM are shown in Table 2.

TABLE II
EXPREMENTAL IM RATED PARAMETERS

Parameters	value
Rated voltage (V)	380
Rated power (W)	270
Supply frequency (Hz)	50
Pole pairs	2
Stator winding connections	Y
Stator winding resistance (Ω)	34.73
Rotor winding resistance (Ω)	32.12
Mutual inductance (H)	1.339
Self-inductance of stator (H)	0.139
Self-inductance of rotor (H)	0.159
Inertia ($kg.m^2$)	0.00161

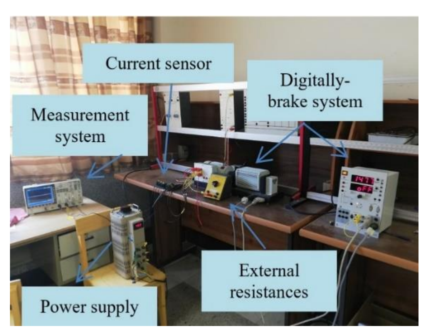

Fig. 4. Test-rig of WRIM used for RAF detection.

B. Fault index analysis with speed control in steady-state condition

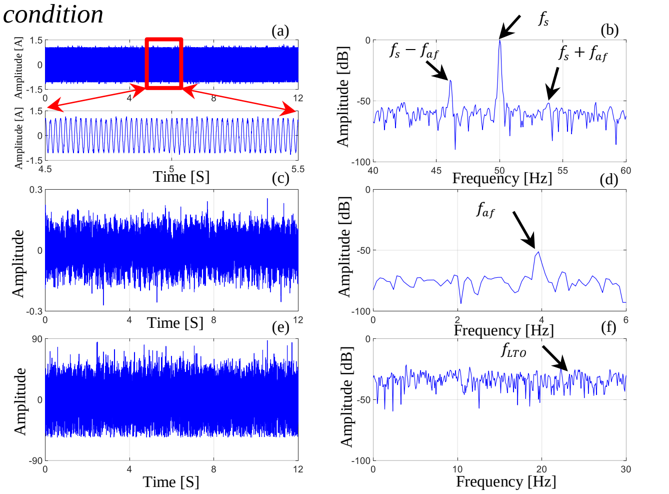

Fig. 5. The results of steady-state condition fault on speed control WRIM. a) stator current signal with asymmetric fault. b) Fourier transform of current signal. c) Amplitude signal that obtained from NFDEO. d) Fourier transform of amplitude signal. e) Phase signal that obtained from NFDEO. f) Fourier transform of phase signal.

It is necessary to note that in the case of controlling the speed of IMs, the amplitude of left sideband related to the asymmetry fault would be considerable in comparison with the right one. Therefore, some previous methods presented in the literature such as [17] cannot be used for fault detection process. In this paper, the proposed method is tested for this scenario.

Fig. 5a shows the signal collected for 12 seconds. It is clear from Fig. 5b that the fault index is completely demodulated from the fundamental frequency in the Fourier space. Since gearbox was not implemented in the drive-train of tested system, rotor speed characteristic frequency (f_s+f_r) is used as LTOs.

C. Fault index analysis without speed control in steady-state condition

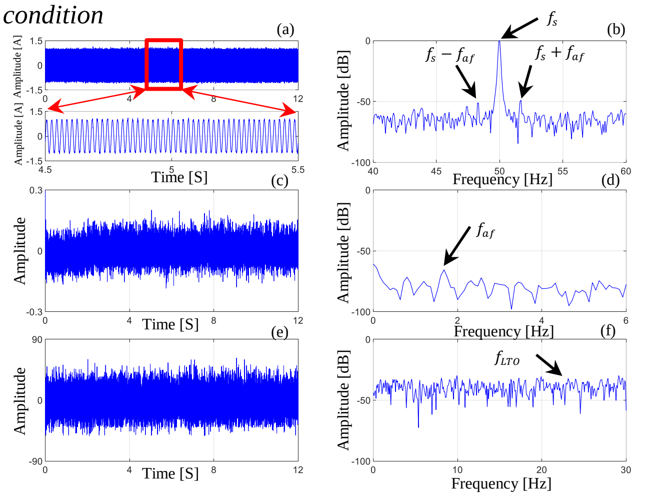

Fig. 6. Results that obtained from the test on the motor with a steady-state fault (without speed control) -a) stator current signal with asymmetric fault -b) Fourier transform of current signal -c) amplitude signal that obtained from NFDEO -d) Fourier transform of amplitude signal -e) phase signal that obtained from NFDEO -f) Fourier transform of phase signal.

The output of NFDEO consists of two signals: 1) amplitude signal and 2) phase signal which are shown in Fig.5c and Fig.5e, respectively. When external resistance is applied to the rotor winding of motor, an asymmetry fault occurs in the motor. Then the asymmetry fault and LTOs indices can be obtained based on the proposed method as shown in Fig. 5d and Fig. 5f.

In this part of our experiments, the WRIM without speed control is used to detect the asymmetry fault index. The effect of not using speed control on the fault intensity on both sides of the fault index is quite visible (Fig. 6b). The asymmetry fault frequency in this test is set at 1.8 Hz. This frequency can be observed in Fig. 6d. It can be deduced that in both test-rig with and without control, rotor asymmetry fault characteristic frequency can be detected correctly. Therefore, it can be concluded that the proposed method effectively separates and demodulates fault from LTOs and supply frequency, respectively. In the presented test-rig, gearbox and reduction coupling is not linked to the shaft of machine, therefore, the effects of low torque oscillation which is related to the rotational speed of machine in the low-speed side of gearbox cannot be detected in the stator spectrum of machine. Therefore, rotational speed of machine (f_r), which emerges in the current spectrum of machine as f_s+kf_r, is considered for this purpose. It is necessary to note that this phenomenon is related to the effects of inherent mix eccentricity of machine.

D. Fault index analysis in Transient condition

The starting moment of motor has not been used for transient analysis and the stator current signal is recorded while a motor is running. Therefore, changes in the motor speed are implemented during the operation of motor for the transient condition analysis. In this part, the motor works in two modes of acceleration and deceleration. Motor speed in acceleration mode increases from 1400 rpm to 1450 rpm and in deceleration mode it decreases from 1450 rpm to 1400 rpm (Fig.7a and Fig.7b). Fig.7c and Fig.7c show the collected signals from the motor in these modes, respectively. The associated amplitude and phase signals can also be observed in Fig.7e, Fig.7f, Fig.7g and Fig.7h, respectively.

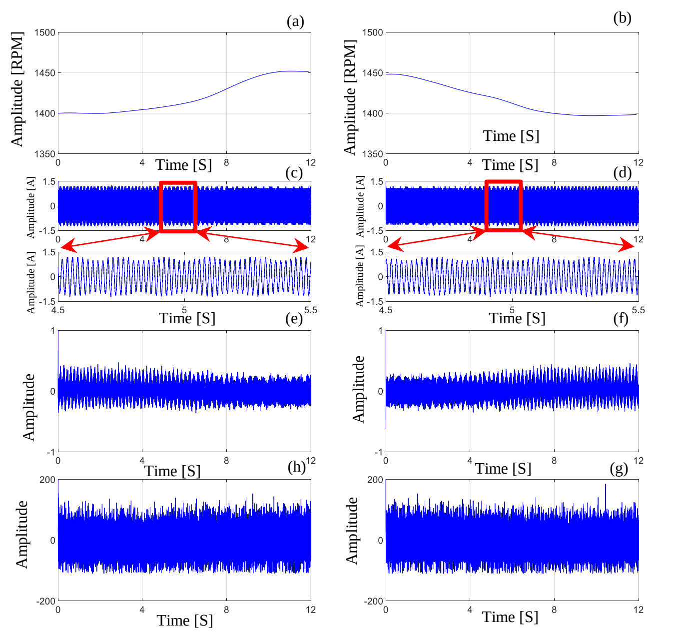

Fig. 7. Time series of stator current signal in transient condition and signal of NFDEO -a) Diagram of velocity changes in positive acceleration mode. b) Diagram of velocity changes in deceleration mode -c) The stator current signal with asymmetric fault in acceleration mode -d) stator current signal with asymmetric fault in deceleration mode -e) amplitude signal for acceleration mode -f) amplitude signal for deceleration mode -g) Phase signal for acceleration mode -h) phase signal for deceleration mode.

After calculating the amplitude and phase signal, the WVD method should be used in the case of transient condition. Then, the fault indices can be observed well which are shown in Fig. 8-c and 8-d. We can see that the fault index in the main signals was never detectable (Fig.8a and Fig.8b), and we need to separate and demodulate the fault signal from the motor current signal.

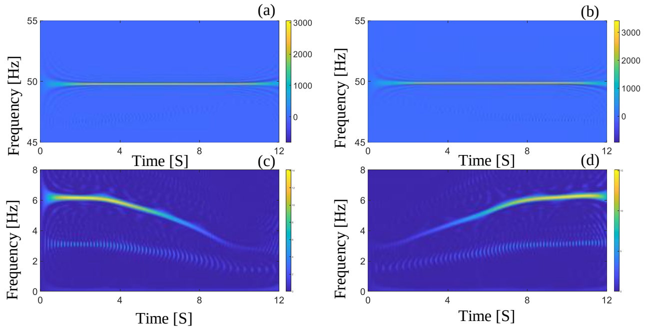

Fig. 8. Wigner distribution for the signals of Fig. 7. a) Wigner-ville distribution for current signal in acceleration mode. b) Wigner-ville distribution for current signal in deceleration mode. c) Wigner-ville distribution for amplitude signal in acceleration mode. d) Wigner-ville distribution for amplitude signal in deceleration mode.

After separating the signals, and using the Wigner-ville distribution, fault is observed in the acceleration and deceleration modes in Figs. 8-c and 8-d, respectively.

If the related frequencies that cause interference in the detection of the RAF index are related to the rotational speed of the machine can be reduced in the spectrum of stator current based on NFDEO method. As a result, the fault index can be identified by removing these effects through the amplitude of the signal which is calculated based on NFDEO and these effects can be detected through phase of stator current signature calculated based on the proposed method. If these effects are related to changes in the amplitude of the signal, there will be a possibility of interference and failure to identify the fault index. It is necessary to note that RAF effects on the amplitude of the stator current signature of machine.

E. Comparison between proposed method and other approaches

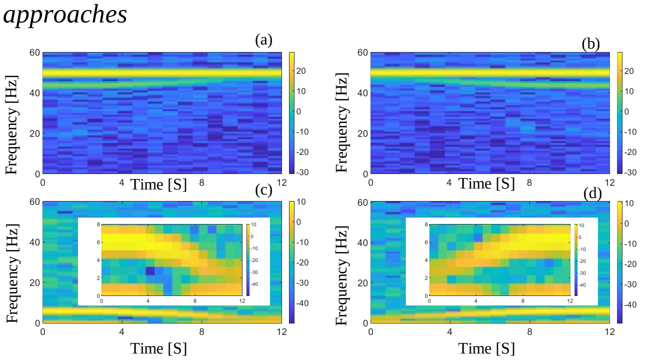

Fig. 9. STFT results for experimental data. a) STFT of current signal in acceleration mode. b) STFT of current signal in deceleration mode. c) STFT of amplitude signal in acceleration mode. d) STFT of amplitude signal in deceleration mode.

In this section, a comparison between the PWVD and short time Fourier transform (STFT) is presented to justify the used of PWVD. It can be seen from the comparison of Figs. 8 and 9, the STFT does not have the ability to detect the fault indices with high resolution as it has been reported in [35].

Another comparison is between the two demodulation techniques and the TKEO strategy. This comparison has been made in two steady-state and transient modes. The experimental data for testing the TKEO method is the same. Deceleration mode of WRIM test is used with the TKEO method in the transient condition. The severity of the fault obtained in the TKEO method, both in the steady state and in the transient state, is lower than the proposed method (Fig. 10). On the other hand, most of the existing techniques for asymmetric fault detection, such as rectified stator current or squared stator current, cannot separate LTO from asymmetric fault.

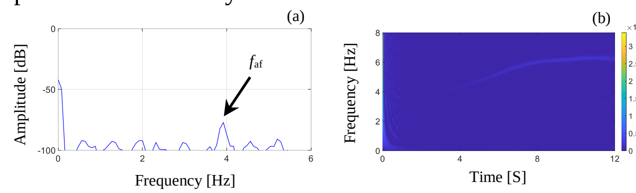

Fig. 10. TKEO result. a) Stator current Spectrum of WRIM based on TKEO approach. b) Wigner-Ville distribution of stator current based on TKEO approach in deceleration mode.

V. Conclusion

In this paper, NFDEO method for asymmetry fault detection in IMs in the presence of LTOs in transient and steady-state conditions based on stator current signal are investigated. In this regard, the method is tested through synthetic signal and experimental results from 0.25 kW WRIM. In order to detect the effects of faults in the transient mode time-frequency method based on PWD is used and the obtained results are compared by STFT to show the validity of presented method. The proposed method can demodulate the index of fault from the supply frequency, which can be useful to eliminate the main component leakage effects. Moreover, the presented method can effectively detect the asymmetry fault and separate it from LTOs. Due to the single-phase current measurement, the proposed method is less complex and hence cost-effective in comparison with previous ones.

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