AUT Journal of Electrical Engineering

AUT J. Electr. Eng., 56(1) (Special Issue) (2024) 37-46
DOI: 10.22060/eej.2023.21583.5483

High-Resolution Rotor Fault Diagnosis of Wound Rotor Induction Machine Based on Stator Current Signature Analyses

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ABSTRACT: Wound rotor induction machine (WRIM) has been extensively used in different applications such as medium-power wind turbines and traction systems. Since these machines work under harsh and difficult conditions, condition monitoring of such systems is crucial. Different electrical and mechanical signatures of machines were used for electrical and mechanical fault detection in electrical machines such as vibration, acoustic emission, stray flux, and stator current signature. In recent years, stator current signature analysis due to simplicity, cost-effectiveness, and availability has been considered for fault detection process in comparison with previous conventional methods such as acoustic and vibration. In this paper, a high-resolution technique based on the chirp-Z transform is used for rotor asymmetry fault (RAF) detection in induction machines through stator current signature analysis. In this regard, the Teager-Kaiser energy operator (TKEO) technique for demodulation fault characteristic frequency is used as a pre-processing stage to avoid leakage of the supply frequency. The method has better accuracy due to better spectral resolution and resolvability. Furthermore, computational complexity in the proposed method will be reduced in comparison to the previous conventional ones which have used the Fast Fourier transform (FFT). The proposed technique is tested through synthetic and experimental stator current of WRIM in healthy and faulty conditions with different rotational speeds and fault severities. The results show the validity of the proposed method in rotor asymmetry fault detection through the stator current signature of WRIM.

Review History:

Received: Jul. 11, 2022
Revised: Oct. 22, 2022
Accepted: Feb. 13, 2023
Available Online: Feb. 01, 2024

Keywords:

Fault detection
Condition monitoring
Stator current signature analysis

1- Introduction

Induction machines (IMs) are preferred in the industry due to their low price and high reliability [1]. Wound rotor induction machines (WRIMs) are of great importance due to their use in wind turbines and traction systems [2]. Mechanical and electrical faults in IMs may be due to imperfect motor manufacturing processes, improper use, and lack of ventilation. Faults in IMs can be classified into three major classes as bearing faults, stator faults, and rotor faults [3]. These faults must be detected as soon as possible, as they will lead to serious and costly damages. These faults lead to unbalanced air gap flux, unbalanced line currents, torque fluctuations, decreased average torque, losses, reduced efficiency, and overheating [4]. According to the mentioned cases, a condition monitoring system is required. In this regard, many technologies related to the condition monitoring of electrical machines have been developed including acoustic emission analysis, vibration analysis, motor current signature analysis, and thermal analysis [5, 6].

In [7], a sensor-based method for detecting broken rotor bar faults in IMs is presented by considering the frequency domain analysis of magnetic flux density variations. In another study [8], the Hall Effect sensor along with the multilayer neural network was used to detect broken rotor bar faults at very low slip. In the field of vibration effect analysis, using a method based on spectral analysis and wavelet functions has been introduced to identify broken rotor bars in squirrel cage induction machines [9, 10]. Motor current signature analysis (MCSA) is another reference method for fault detection of induction motors. This method relies on detecting the spectral component of faults in the stator current signature. MCSA detection systems are based on stator current sampling, analyses of the spectrum, and detection of fault-related indices [11]. In the field of MCSA, an artificial neural network is used to detect broken rotor bar faults based on the Hilbert transform [12]. In [13], discrete wavelet transform is used to calculate the energy associated with the rotor faults after extracting the envelope of stator current by means of Hilbert transform. One of the challenges in MCSA is the detection of RAFs in very low slips. In this regard, a method has been proposed to reduce spectral leakage in stator currents in low slips [14, 15].

Among the proposed methods, those based on MCSA have more advantages due to the minimum number of measured variables and the lack of need for multiple sensors. On the other hand, stator current measurement is required for other

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purposes such as machine protection and control systems [16-17].

One of the major problems in detecting fault harmonics in MCSA is the presence of the main frequency component of sources. Due to spectral leakage caused by a mismatch between the desired frequency component and chosen frequency resolution, time limits, and observation, it the frequency component can be buried by vicinity frequencies. In this regard, a simple method is proposed to eliminate the main harmonic effects before performing the current spectral analysis. The proposed method is based on a nonlinear filter named as Teager Energy Operator (TKEO). TKEO only operates on three consecutive instances of the current samples, which makes it almost instantaneous. This operator converts the main harmonic of the source into a fixed component that can be easily removed. In addition, the method significantly reduces computational costs and hardware requirements compared to other methods [18, 19]. Several papers have been presented in the field of rotor asymmetry fault (RAF) in wound rotor induction machines (WRIM). In this regard, the detection of RAF in the presence of low-frequency torque oscillations (LTOs), which is caused by the presence of speed reducer couplings or gearboxes, has been done in transient and steady-state conditions. The results show that it is possible to separate RAF from the LTOs by adopting a suitable method [11, 15]. Furthermore, RAF detection of WRIM in different loads as well as the intensity of faults by means of recursive fault detection technique shows that RAF can be detected properly and with high accuracy at speeds higher than the no-load speed [19].

In TKEO algorithm, first, the tested signal is applied, and then the diagnostic signal is calculated. In the next step, the diagnostic signal spectrum is calculated by FFT and finally, the diagnostic signal spectrum is evaluated [15]. To monitor the condition of electric motors, calculating the spectrum of a narrow band of current spectrum in the desired resolution is necessary. The standard fast Fourier transform (FFT) followed by the TKEO provides very large global spectral information. Therefore, the Chirp-Z transform (CZT) and Gortzel's generalized algorithm (GAA), were introduced as alternatives to Fourier transform. The chirp-Z transform is much more efficient in calculating the larger bandwidth spectrum compared to FFT and GAA methods. It is necessary to note that considering the operational slip range of IMs, a certain bandwidth spectrum compared to Fourier transform methods and GAA is desired to detect the effects of RAFs in the spectrum of stator current signature. Thus, to achieve high resolution at a certain bandwidth, the CZT is used as an alternative to the FFT. In order to reduce the effects of spectral leakage due to the presence of main harmonics, TKEO technique is used as a pre-processing technique [20].

In the next sections, the energy operator will be introduced, and then the GAA and CZT will be discussed and the reasons for the superiority of CZT will be explained. Next, the proposed method is first tested on synthetic data and then data obtained from the stator current of studied WRIG in which an RAF is applied, the validity of this method will be evaluated.

2- Problem Description

Fault detection in electric machines by means of stator current signals is difficult due to the modulation of fault indices with the characteristic frequency of the supply signal. In other words, the characteristic frequencies appear as sidebands around the power supply frequency (f_s). The frequency components of RAF in the spectrum of stator current can be detected at ($1\pm2ksf_s$) where k=1, 2,…. In this regard, in very low slips the characteristic frequency of RAF gets closer to the supply frequency. Therefore, the leakage of the supply frequency leads to burying the characteristic frequency of RAF. To solve this issue, the modulation of RAF from supply frequency leads to isolating and separating RAF characteristic frequency from supply frequency. The first goal of this paper is to demodulate the RAF characteristic frequency from supply frequency. On the other hand, in current spectrum of machines other frequencies such as low torque oscillations (LTOs) leads to false alarm and may generate similar characteristic frequency around the supply frequency. Consequently, stator current spectrum with high resolution is need to detect RAF in low sampling frequency.

The interval of variations in the 1st harmonic of RAF characteristic frequency for the left and the right sidebands are equal to [(1-2$s_n f_s$) f_s] and [(1+2$s_n f_s$) f_s], respectively (s_n: nominal slip). When RAF index is demodulated from the supply frequency, the interval of fault characteristic frequency is not in the mentioned intervals. In this case, RAF characteristic frequency can be observed in the interval of [0 (2$s_n f_s$)]. In this paper, a method which has high resolution for separation of existing frequencies in the desired interval is considered.

3- Proposed Technique for Rotor Fault Detection in Induction Machine

In this section, the proposed method for RAF detection in IMs is presented. The proposed method pursues two goals: one: to demodulate the RAF index from supply frequency and the second is to detect the RAF index using a high-resolution method. In the following, the method of CZT is explained and the reason for using the CZT method is investigated. According to the best knowledge of the authors of this paper, the proposed method for fault detection in electric machines has not been studied, so far.

3- 1- Teager-Kaiser Technique

The mathematical definition of the TKEO energy operator, its effects on the stator current of healthy and faulty machines, and the application of this operator in motor fault detection have been well explained in previous studies [18]. The continuous form of TKEO, which is applied to a continuous-time signal of x(t), is:

$$\psi[x(t)] = \dot{x}(t)^2 - x(t)\ddot{x}(t) \quad (1)$$

In general, TKEO is defined as follows for a discrete signal.

$$\psi(x[n]) = x[n]^2 - x[n-1]x[n+1] \quad (2)$$

TKEO can be obtained through simple mathematical operations as (2) where three samples of studied signal ($x[n$-1], $x[n]$, x [n+1]) can be used to calculate each sample of TKEO function. Therefore, it has low computational complexity. The modulated current obtained by computation of TKEO operator is the sum of three components as a fixed, a dominant, and two oscillating terms. To eliminate the negative effect of the DC component of the obtained signal corresponding to the main harmonic of the supply system, a new diagnostic signal is defined as follows:

$$i_{TK}(t) = \frac{\psi(i(t)) - \overline{\psi(i(t))}}{\overline{\psi(i(t))}} \quad (3)$$

i_{TK} (t) is a AC component of $\psi(i(t))$ which is normalized by dividing to the dc component.

3- 2- Chirp-Z Transform

Chirp-Z transform is a method used to calculate a limited range of spectral frequencies in the spectrum of signals that are linearly distributed over a certain range [19-22].

The z-transform of a discrete signal can be written as

$$Y(z) = \sum_{n=-\infty}^{\infty} y(n) z^{-n} \quad (4)$$

If the signal $y(n)$ is zero for n<0, (4) can be modified as follows:

$$Y(z) = \sum_{n=0}^{\infty} y(n) z^{-n} \quad (5)$$

The Discrete Fourier Transform (DFT) of a discrete signal with a limited number of samples (L) is given as (6).

$$Y(z) = \sum_{n=0}^{L} y(n) e^{-j\omega n} \quad (6)$$

It can be found out from (5) and (6), DFT can be considered as Z-transform along with unit circumference. However, CZT computes Z-transform along with a general spiral contour in

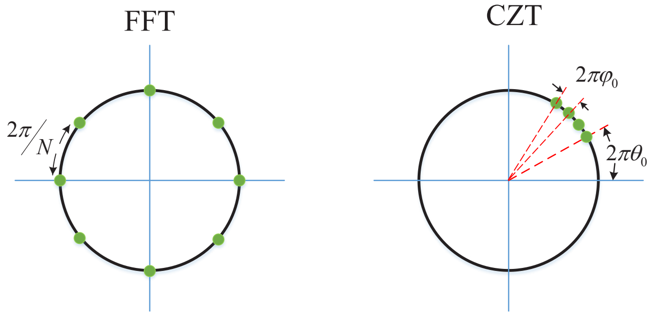

Fig. 1. Z-plane unit circle representation of FFT and CZT

the Z-plane. The counter with specified starting point (A) and length of arc (ω) can be calculated as follows:

$$z_k = A\omega^k,\ k = 1, 2, \ldots, M \quad (7)$$

The FFT of a signal is calculated at equidistant points along the unit circle of Z-plane. To overcome this problem, the CZT technique can be used. It is necessary to note considering A=1 and ω= $\omega_0 e^{j2\pi\varphi 0}$, the CZT equations are equal to FFT. In other words, CZT is the general form of FFT. Unlike the FFT, CZT is calculated in the small section of the unit circle on the z-plane which spirals in or out depending on the value of ω (Fig.1).

The values of A and ω which describe the Z-plane contour, are given as follows ((8),(9)).

$$A = e^{\left(\frac{j2\pi f_L}{f_s}\right)} \quad (8)$$

$$W = e^{\left(\frac{-j2\pi(f_U - f_L)}{Mf_s}\right)} \quad (9)$$

The main advantage of CZT is that it can be calculated for a number of points along the counter. This will be convenient for analyzing the spectrum in a certain frequency region. In this regard, two sin wave signals with the frequency of f_1=4 Hz and f_2=5 Hz are considered to show the priority of CZT in comparison with DFT for calculating the spectral frequencies in the specific frequency region. The synthetic signal introduced for comparison between DFT and CZT is given in (10) (Fig.2a).

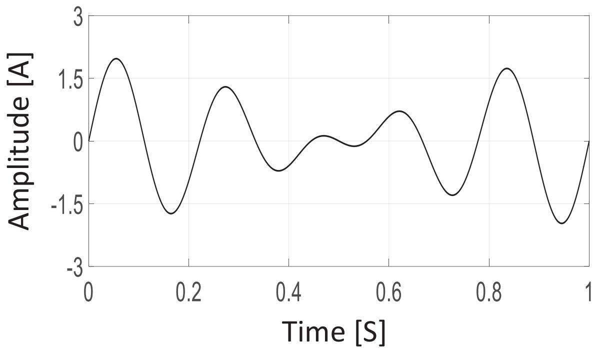

Fig. 2. The synthetic signal presented in (8) used for comparing the spectrums obtained through FFT and CZT techniques for f1=4 Hz and f2=5 Hz.

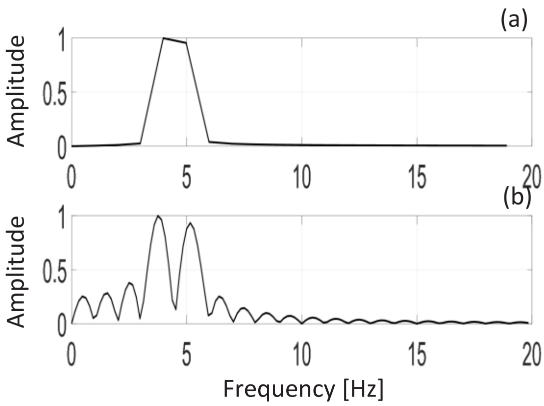

Fig. 3. Spectrums of synthetic signal –a) FFT –b) CZT.

$$y(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) \tag{10}$$

The sampling frequency is 200 Hz and the data is recorded for 1S (Fig.2). In order to compare the presented method with FFT which has Hanning windows, the synthetic signal with limited samples is required. In the presented synthetic signal only two frequencies (4 Hz and 5Hz) are defined, however, in the real signal the number of presented frequencies is not limited. Therefore, the time and the number of samples are defined 1 S with a frequency of 200 Hz deliberately. As can be observed, the DFT of the signal cannot discern two frequencies in the spectrum of stator current (Fig.3a). However, CZT focuses on the zone of interest. The results show that both frequencies of sinusoidal functions presented in (10) can be detected properly by means of the CZT algorithm (Fig.3b).

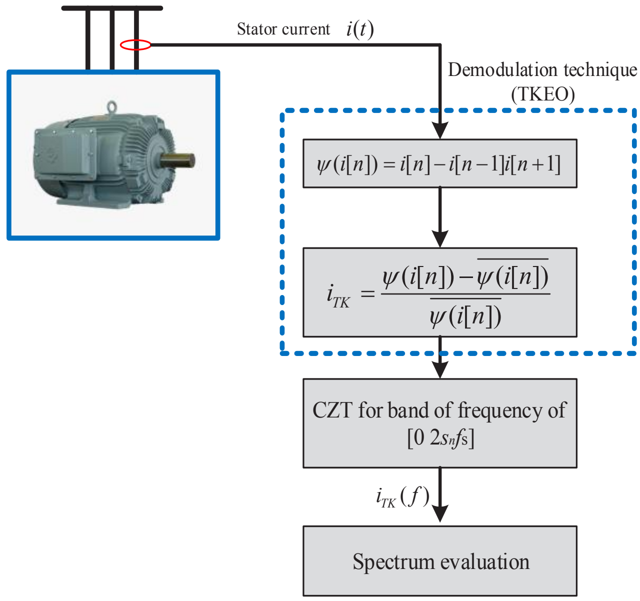

Fig. 4. Proposed technique for fault detection in IMs.

3- 3- Flowchart of proposed method

The two goals of this paper can be obtained through a combination of TKEO method as the pre-processing stage and CZT. In this regard, the normalized signal of TKEO is responsible for demodulating the fault characteristic frequency from the main supply frequency to avoid leakage effects of the fundamental frequency. Then, by means of CZT, the high resolution of the frequency spectrum in a specific frequency range is obtained. Since the variation of slip depends on the nominal rotational speed of the machine, the interval frequency band as [0 $2s_n f_s$] is considered for CZT algorithm. The flowchart of the proposed technique is given in Fig.4.

4- Results

The proposed method in this paper is evaluated in this section in the field of analysis by means of synthetic signals and experiments. Then, the proposed method is compared with conventional FFT.

4- 1- Analytical results

In order to detect the RAF in the spectrum of stator current, a synthetic signal is presented to analyze the behavior of the proposed method. It is necessary to note that RAF leads to amplitude modulation (AM) of RAF characteristic ($2sf_s$) which can emerge as sidebands in the vicinity of the main frequency (f_s).

The concept of RAF as AM in the stator current of IMs can be modeled as a synthetic signal in the form of (11).

Table 1. Parameters of WRIM

Column heading	Value
Rated Power	270 (W)
Rated Voltage	380 (V)
Poles	4
Supply frequency	50 (Hz)
Rated speed	1360 (RPM)

$$i_{s\_f} = I_s \cos(2\pi f_s t)\left[1+\gamma\cos(2\pi(2skf_s)t)\right], k=1,2,3,... \quad (11)$$

where γ and I_s are fault severity index and the maximum stator current of IM, respectively. With considering the first harmonic of RAF, (11) can be rewritten as (12).

$$\begin{aligned} i_{s\_f} &= I_s\cos(2\pi f_s t) + \frac{\gamma}{2} I_s \cos(2\pi(1-2s)f_s t) \\ &+ \frac{\gamma}{2} I_s \cos(2\pi(1+2s)f_s t) \end{aligned} \quad (12)$$

To consider the effects of leakages on the frequencies close to the fault characteristic frequency, other sidebands ($f_s \pm f_{Add}$) are added in the vicinity of the fault characteristic frequency in the synthetic signal presented in (12), as (13) ($i_{s\_f\_New}$). The amplitude of the additive frequencies added as sidebands to the main frequency is considered equal to the value of fault indices ((γ/2)I_s) to testify to the validity of the proposed method.

$$\begin{aligned} i_{s\_f\_New} &= I_s\cos(2\pi f_s t) + \frac{\gamma}{2} I_s \cos(2\pi(1-2s)f_s t) \\ &+ \frac{\gamma}{2} I_s \cos(2\pi(1+2s)f_s t) + \frac{\gamma}{2} I_s \cos(2\pi(f_s - f_{Add})t) \\ &+ \frac{\gamma}{2} I_s \cos(2\pi(f_s + f_{Add})t) \end{aligned} \quad (13)$$

The time series of synthetic signal used for fault detection with the sampling frequency of 1k obtained for 10 S is given in Fig.5a. The spectrum of the synthetic signal with s=0.02, I_s=1, γ=0.005 is given in Fig.5b in which sidebands of fault characteristic frequencies ($f_s \pm f_{RAF}$) emerge in vicinity of sidebands of additive frequencies ($f_s \pm f_{Add}$) where f_{RAF}=2 Hz and f_{Add}=3 Hz.

It is worth mentioning that the spectrum of the synthetic signal in the frequency domain is obtained through FFT of the signal obtained for 10 S. To overcome the leakage effects in

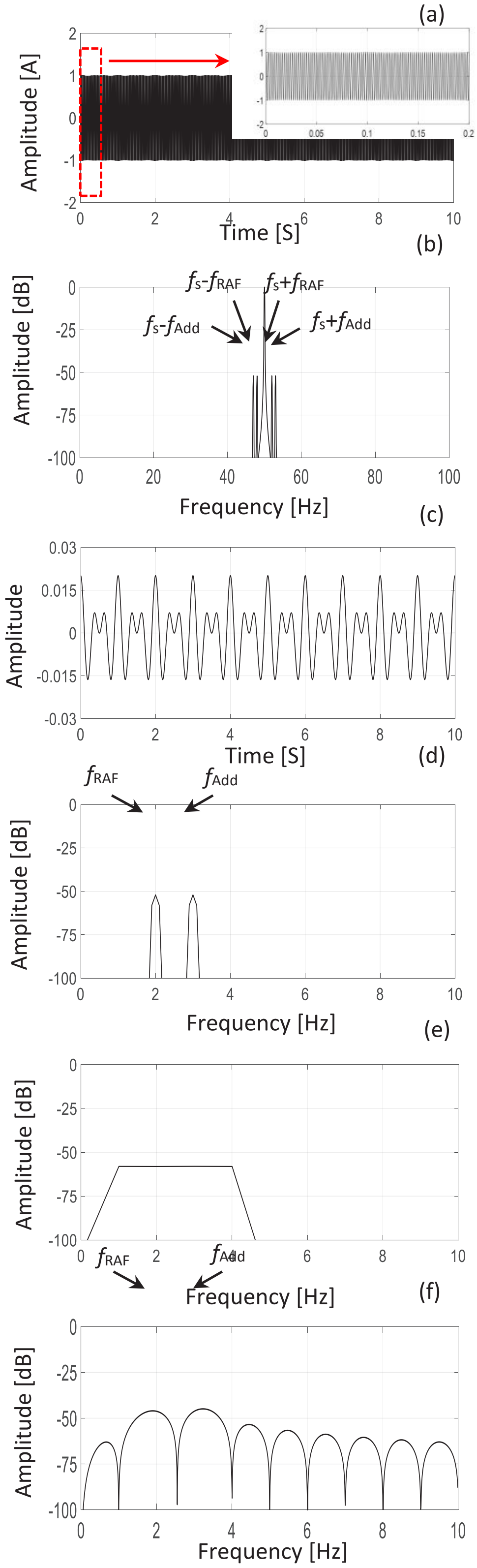

Fig. 5. Results obtained through synthetic signal including rotor asymmetry fault and additive frequency close to RAF–a) Time-domain of synthetic signal for 10S –b) FFT of synthetic signal for 10S -c) TKEO of synthetic signal for 10S -d) FFT of TKEO of synthetic signal for 10S -e) FFT of synthetic signal for 1S -f) CZT of TKEO of synthetic signal for 1S

FFT of the signal, Hanning windows is used for the obtained spectrum in the frequency domain (Fig.5b). It is necessary to note that in machines with low slips, the sidebands related to the fault get closer to the fundamental frequency. Therefore, separation and isolation of fault characteristic frequency is inevitable. In this regard, the demodulation technique such as TKEO presented in this paper can be useful. The time domain of TKEO of synthetic signal is given in Fig.5c. It can be found out the TKEO can demodulate the frequencies of sidebands in the frequency domain (Fig.5b). The FFT of TKEO for 1 S with Hanning windows is given in Fig.5e. As it can be observed, separation between the frequencies of f_{RAF} and f_{Add} even with Hanning windows cannot be possible. In this regard, the CZT of TKEO is given in Fig.5f. It can be easily found that the frequency of fault can be tracked in the spectrum of the signal. It can be deduced that in FFT even with Hanning windows the capability for the detection of fault indices is reduced and on the other hand the volume of calculation increases which makes the proposed combination of TKEO technique and CZT algorithm effective in RAF detection procedure.

4- 2- Experimental results

The presented method is validated through experiments by means of test-rig including WRIM linked to the digital-brake system. The digital brake system is used to emulate the variation of rotational speed due to mechanical loads (Fig.6). The parameters of WRIM used for fault detection are given in Table I. In order to prove the efficacy of the presented method, the results obtained in the steady state of healthy and faulty conditions are analyzed. In this study, the RAF is considered where these faults include the major part of mechanical faults that occurred in induction machines. The inter-turn fault in WRIM leads to a rise in the resistance of the phase in which the fault is occurred. Since the thermal increase in resistance of one phase of WRIM due to current unbalance relative to the other windings will give the same effect as a single turn short

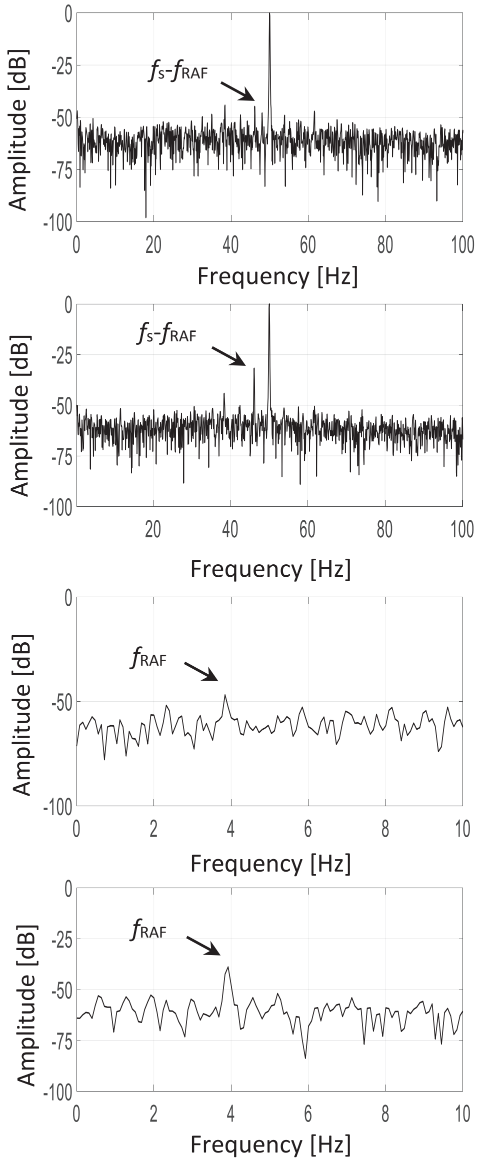

Fig. 7. FFT of stator current signature of WRIM in case of –a) Healthy –b) Faulty –c) TKEO of stator current in the case of healthy WRIM –d) TKEO of stator current in the case of faulty WRIM (s=0.0388 .

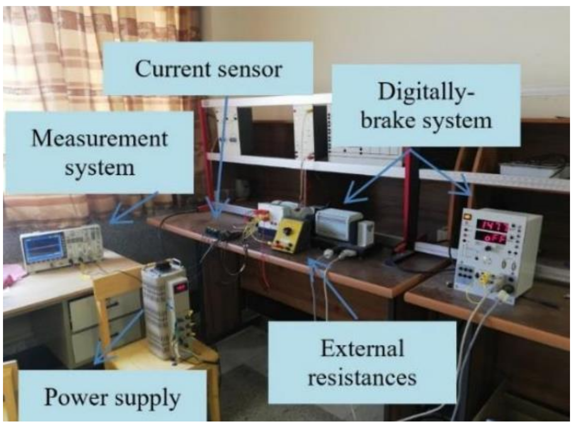

Fig. 6. Test-rig dedicated for rotor asymmetry fault in IMs.

circuit. For the motor used in [23], this is about 17% increase, which is equal to a 42.5 ◦C increase in the temperature of one winding in comparison to the other two windings. Therefore, in this paper to emulate the effects of RAF, external resistance is inserted into the rotor winding of the machine. The obtained results are analyzed in the MATLAB environment software. In each test, 25k samples with a frequency of 2k is recorded. In this paper, external resistance with the magnitude of 0.147 p.u is import to the rotor circuit of WRIM. The spectrum of stator current in healthy and faulty conditions is given in Fig.7a and Fig.7b, respectively. In order to demodulate the fault characteristic frequency from the fundamental frequency, the TKEO of the healthy and faulty signals are given in Fig.7c and Fig.7d, respectively. All 25k samples with a sampling frequency of 2k are used for the analysis of stator current based on FFT with Hanning windows. The major problem of the technique presented based on FFT is related to the volume of calculation and isolation of fault in the presence of other frequencies close to the fault characteristic frequency with lower samples.

The FFT and CZT of stator current signal for 10 S in healthy (s=0.0388) and two faulty cases (s=0.0388 and s=0.0267) with two different fault severities (R_{unb}=0.147 p.u and R_{unb}=0.029 p.u) are given in Fig.8. It can be found out the CZT technique along with TKEO can isolate the fault characteristic frequency in a specific band of frequency as it is given in Fig.8d ([0Hz 10Hz]).

Since the nominal rational speed of the machine and consequently the nominal slip can be obtained, the band of frequency for CZT algorithm can be obtained. However, in this paper, the spectrum of signal through CZT algorithm is given in the interval of [0Hz 10Hz]. In the presence of frequencies close to the characteristic frequencies with equal values, the efficacy of FFT will reduce as it has been proved through the synthetic signal given in Fig.2a and Fig.5e. It has been shown that the first harmonic of rotor asymmetry fault (RAF) (1±2sfs) has the highest amplitude and the rest of the harmonics have far smaller amplitudes than the first harmonics, and as a result, detecting other harmonics is practically difficult and to some extent not possible, that's why in this paper, other harmonics are not considered and cannot be detected in the spectrum of stator current signature.

The experiments are carried in two different rotational speeds (s=0.0388 and s=0.0267) with different fault severities (R_{unb}=0.147 p.u and R_{unb}=0.029 p.u) forced by a digital brake system linked to the shaft of WRIM in healthy and faulty conditions. It can be deduced that by increasing the rotational speed of the machine the amplitude of fault decreases (Fig.8e and Fig. 8f). In order to compare the results obtained through faults from healthy cases, the results of stator current obtained from healthy cases are given in Fig.8a and Fig.8b. This issue can be easily observed in both fault cases. It can be notable that in high rotational speed 1460) or low slip (s=0.0267) the performance of the CZT technique can be obtained through Fig.8f where the fault characteristic frequency are clearly isolated from the vicinity frequency. Since the supply frequency is not constant, the TKEO pre-processing method for demodulation of RAF characteristic frequency is used. In fact, the TKEO pre-processing method does not depend on the place of the main harmonic of supply frequency. In other words, the method demodulates the harmonic of fault from the main component of the supply frequency and then transfers it to the zero frequency (DC value). By means of normalization technique, the DC value can be easily eliminated in the spectrum of stator current. The variation of the main frequency leads to the leakage effects in the spectrum especially in low slips. As a results, the effects of RAF can be easily detected. Therefore, the presented method can even be used for inverter-fed induction machines.

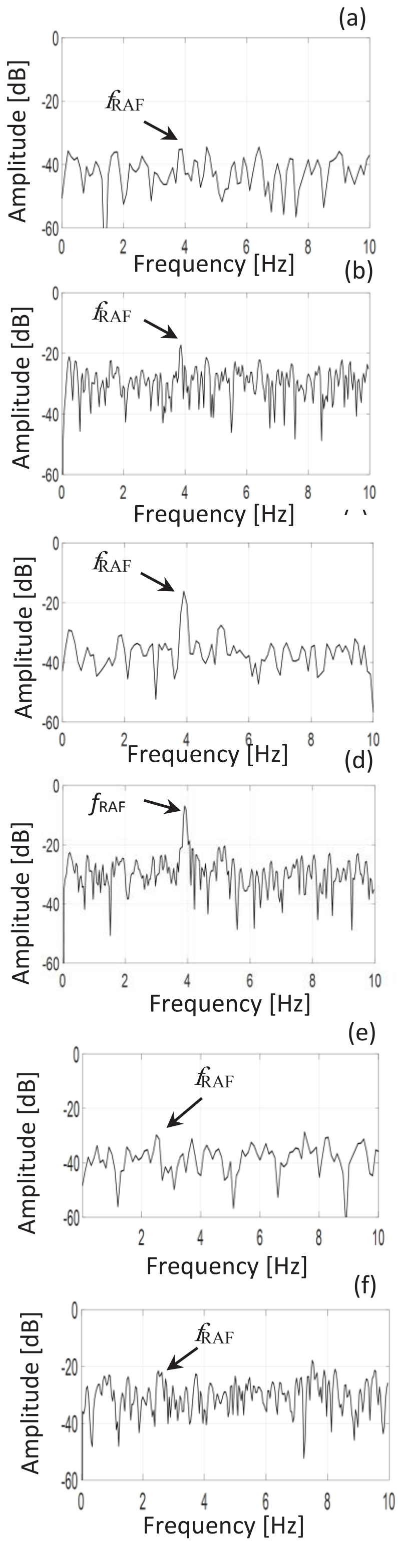

Fig. 8. Frequency-domain of TKEO of stator current signature obtained from faulty WRIM (s=0.0388 with Runb=0.147 p.u) -a) FFT of stator current signature in healthy case –b) CZT in healthy case –c) FFT in faulty case and –d) CZT in faulty case –e) FFT in faulty case for s=0.0267 and Runb=0.029 p.u. -f) CZT in faulty case for s=0.0267 and Runb=0.029 p.u.

5- Conclusion

In this paper, a high-resolution technique based on CZT is presented. Since CZT has priority in complexity and the volume of calculation in comparison with conventional FFT even with Hanging windows, fault diagnosis based on CZT is investigated. In this regard, the synthetic signal including the effects of RAF and main supply harmonic is considered. It is necessary to note that RAF characteristic frequency emerges as an additive frequency around the supply frequency which is affected by the leakage of supply frequency. To overcome this issue, TKEO technique as a demodulated technique is used for this purpose. The experimental results show that the fault characteristic frequency can be observed in the demodulated signal by means of CZT in narrow band frequency. It is worth mentioning that the line start machine operates in the narrow band slip which can be obtained based on the nominal speed of IMs.

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HOW TO CITE THIS ARTICLE

R. Ghadirinezhad, M. Hoseintabar-Marzebali, High-Resolution Rotor Fault Diagnosis of Wound Rotor Induction Machine Based on Stator Current Signature Analyses. AUT J Electr Eng, 56(1) (Special Issue) (2024) 37-46.

DOI: 10.22060/eej.2023.21583.5483