

Vold-Kalman Filter Order Tracking for the Detection of Stator Fault in Vector Controlled Induction Motor

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ABSTRACT:

It is well-known that the stator Inter-Turn Short Circuit (ITSC) fault detection in vector-controlled Induction Motor (IM) is a very difficult task so far. This is due to the various problems encountered in diagnostic processes resulting from the speed variation and its influence on electrical signals. As a solution, this paper proposes an approach based on the Vold-Kalman Filter Order Tracking (VKF-OT) technique. To this end, stator phase current, quadrature current and rotational speed were monitored at various speeds with and without fault (i.e. healthy and with the ITSC fault) in the Field oriented control (FOC) IM drive. The VKF-OT technique was applied to the monitored currents in order to track the related harmonic components fault, the results are compared to the classical Fourier analysis (FFT). The obtained results proved that the presented approach is more efficient than the FFT technique, especially when the IM is operating under non-stationary speed conditions.

KEYWORDS: Induction Motor, Field Oriented Control, Vold-Kalman Filter Order Tracking, Fault Diagnosis, Stator Inter-Turn Short Circuit Fault.

1. INTRODUCTION

During the past 3 decades, the subject of monitoring and fault diagnosis of rotating electrical machines has received special attention, due to the increasing industries requirements in terms of production quality, reducing maintenance costs and prevention of unexpected shutdown [1], [2]. In industrial sectors, Induction Motors (IMs) are the most used electromechanical energy conversion devices, representing around 85% of the whole installed motors [3], because of their robustness, simplicity of construction, low cost and stable operation [4]. Generally, these motors are operated under various types of stresses, which can induce different faults, such as eccentricity, broken rotor bar or end-rings, and stator winding fault [5].

According to several studies, more than 30% of IM faults are due to defects in the stator winding [6]–[8]. These faults starts as an insulation breakdown between two adjacent turns in a coil for the same phase (called “Inter-Turn Short Circuit” fault) [9], which do not have great physical signs, but it can induce more serious stator faults in a brief period of time, as phase-to-phase and phase-to-ground faults and eventually the complete

deterioration of the motor [7]. Therefore, early detection of ITSC fault has become of paramount importance. For this purpose, a great number of techniques for the detection of ITSC fault have been proposed in the literature including torque Analysis [10], voltage Analysis [11], instantaneous power Analysis [12], Park’s vector Analysis [13], negative sequence current analysis [14], vibrations analysis [15] and the well-known Motor Current Signal Analysis (MCSA) [16], [17].

Unfortunately, those previously presented diagnostic techniques are still inadequate when the motor is included in a complex control system based on direct torque control and field oriented control [18]. This is due to the control loop strategy and its parameters that affect motor currents and voltages, thus masking the fault effect [19]. In this fact, some researchers have studied the subject to find a solution to this problem. In [20] two different techniques are presented for the diagnosis of the ITSC fault in Direct Torque Control (DTC) IM drive. The first one is the MCSA technique, while the second one is based on the multiple reference frames theory. In [21] the impact of control on faulted IM behavior is studied. The obtained results demonstrate that the

diagnostic indexes habitually used for open-loop systems are no longer effective and the field current component can be used as an effective diagnostic quantity in the case of FOC IM drive. In [22] an approach to detect and locate the ITSC fault in a multiple motor drive system based on the impedance identification technique is proposed. In [23] the Extended Kalman Filter algorithm (EKF) and Extended Luenberger Observer (ELO) are applied to estimate the stator resistance in the case of stator ITSC fault diagnosis of Direct FOC IM drive. In [9], [24] an approach based on an analysis of the internal signals from the control structure is proposed. The increase of the third harmonic amplitude present in the internal control and decoupling signals is used as an indicator to detect the stator faults. Although these presented techniques have proved their effectiveness for the diagnosis of SC faults in a closed-loop system, they do not always achieve good results in the case of non-stationary signals because of their sensitivity to sudden load and speed variations.

In order to solve the problem of ITSC fault detection in vector controlled IM operating under non-stationary speed conditions; a novel diagnosis approach is proposed in this paper, based on the analysis of the $3f_s$ amplitude of the stator current and $2f_s$ amplitude of the quadrature current I_{qs} . Moreover, the Vold-Kalman Filter order tracking (VKF-OT) technique is applied to track the harmonics of interest for the detection of the ITSC fault. The choice of the VKF-OT technique is due to its simplicity and its ability to track and extract the order/harmonic of interest. Contrary to other time-frequency techniques such as wavelet transform analysis that has not provided an ideal filtering process, due to the overlap between adjacent frequency bands [18]. On the other hand, the VKF-OT technique was applied successfully for the detection of stator fault in a surface-mounted permanent magnet synchronous motor [25].

2. THE VOLD-KALMAN FILTER ORDER TRACKING

Order tracking (OT) is considered as one among the most important techniques in vibration analysis. Its main advantage compared to other analytical techniques is its ability to clearly identify non-stationary vibration and easy noise analysis of components which vary in amplitude and frequency influenced by the rotational speed of the reference shaft. OT can be performed by many different ways each of them presenting advantages and disadvantages. According to Blough [26], the most and widely used order tracking techniques are: the Fourier transform based order tracking (FT-OT), the Angular domain order tracking (AD-OT) and the Vold-Kalman Filter order tracking (VKF-OT). This last technique is distinguished from the other order tracking

techniques by its ability to extract the temporal history of a specified order from the measured data with its amplitude and phase.

The VKF-OT is a technique developed by Vold and Leuridan in 1993 [27], which overcomes many limitations of other order tracking techniques, such as allowing the waveforms reconstruction, and high resolution order tracking performance. Moreover, Vold [28] developed and improved this filter in the VKF-OT of the second generation which is well known for its ability to be formulated with different numbers of poles (generally range from 1 to 4) in order to change its bandwidth characteristics. This second generation filter can be applied either as an iterative process or direct solution to allow separation of close or crossing orders. It is important to note that the filter bandwidth selection is the most important part of the VKF-OT analysis especially in the case of induction motors where the harmonic frequency is depended not only on the speed but also on the load. More details can be found in reference [29], [30].

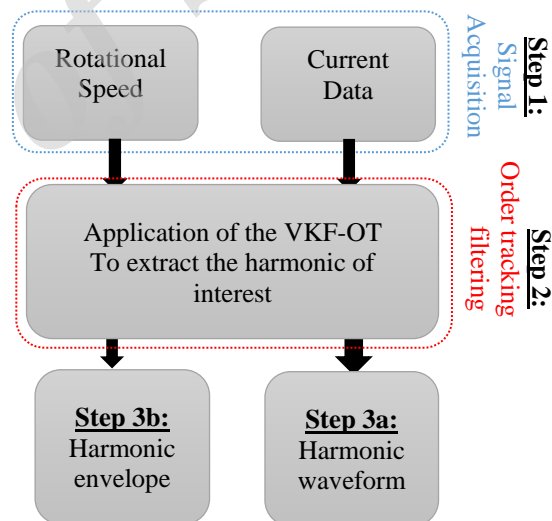


Fig. 1. The VKF-OT technique diagram.

3. MODELLING OF THE INDUCTION MOTOR

In order to study the effectiveness of the proposed diagnostic technique and its ability to detect SC faults under varying speeds conditions, it is necessary to have an accurate model to predict the IM performance and extract fault signatures. To this end, a three-phase squirrel cage IM is considered. Its stator is comprised of three phase concentric windings, while its rotor consists of conductor bars regularly distributed at the periphery of the rotor and connected to each other by two short-circuit rings. To develop our model, each stator windings is treated as a separate coil and the rotor cage is considered as a system of $(n + 1)$ Loops [31]–[34].

3.1. Stator Voltage Equations

The stator equations of the IM can be written as follows [32], [34], [35]:

$$[V_s] = [R_s][I_s] + \frac{d}{dt}[\Phi_s] \quad (1)$$

Where

$$[V_s] = \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}, [R_s] = \begin{bmatrix} R_{sa} & 0 & 0 \\ 0 & R_{sb} & 0 \\ 0 & 0 & R_{sc} \end{bmatrix}, \quad (2)$$

$$[I_s] = \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix}, [\Phi_s] = \begin{bmatrix} \Phi_{sa} \\ \Phi_{sb} \\ \Phi_{sc} \end{bmatrix}$$

And

$$[\Phi_s] = [L_{ss}][I_s] + [L_{sr}][I_r] \quad (3)$$

The matrix $[R_s]$ is a diagonal 3×3 matrix consists of resistances of each coil ($R_{sa} = R_{sb} = R_{sc} = R_s$, under normal operation condition).

Due to the rule of conservation of energy, the stator inductances matrix $[L_{ss}]$ is a symmetric 3×3 matrix. The mutual inductances matrix $[L_{sr}]$ between the stator coils and the rotor loops is a $3 \times n$ matrix.

$$[L_{ss}] = \begin{bmatrix} L_{fs} + L_{ms} & -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & L_{fs} + L_{ms} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} & L_{fs} + L_{ms} \end{bmatrix} \quad (4)$$

and

$$[L_{sr}] = [L_{rs}]^T = \begin{bmatrix} L_{ar1} & L_{ar2} & \cdots & L_{arn} & 0 \\ L_{br1} & L_{br2} & \cdots & L_{brn} & 0 \\ L_{cr1} & L_{cr2} & \cdots & L_{crn} & 0 \end{bmatrix} \quad (5)$$

Where L_{fs} and L_{ms} are respectively the leakage and the magnetizing inductances of the stator.

3.2. Cage Rotor Voltage Equations

The rotor loops voltage equations can be written as follows [32], [34], [35]:

$$[V_r] = [R_r][I_r] + \frac{d}{dt}[\Phi_r] \quad (6)$$

Where

$$[V_r] = [V_{r1} \ V_{r2} \ \cdots \ V_{rm} \ V_{re}]^T, [I_r] = [I_{r1} \ I_{r2} \ \cdots \ I_{rm} \ I_{re}]^T \quad (7)$$

Assuming the cage rotor end ring voltage, $V_e = 0$, and the rotor loop voltages $V_{rk} = 0$ ($k = 1, 2, \dots, n$). The rotor flux linkages $[\Phi_r]$ matrix, can take the following form:

$$[\Phi_r] = [L_{rs}][I_s] + [L_{rr}][I_r] \quad (8)$$

3.3. Mechanical Equation

The mechanical equation of the IM is written as follows [32], [34]–[36]:

$$\frac{d\Omega_m}{dt} = \frac{1}{J}(C_{em} - C_r), \quad \Omega_m = \frac{1}{P} \frac{d\theta}{dt} \quad (9)$$

Where C_{em} , C_r , Ω_m and J are respectively the electromagnetic torque produced by the motor, the load torque, the mechanical speed and the inertia of the rotor.

3.4. Modelling the Stator Fault

In this section, the ITSC fault in a single stator phase is modelled using the same approach described in detail in [20], [37], [38].

For this purpose, a number of N_{sh} turns of the phase “a” are supposed short-circuited and the total number of turns in each phase is equal to N_s . The short-circuited section is defined as “sh” and is introduced in the IM model governing the studied system [39], [40]. Hence, the stator equation of the IM given in Eq. (1) does not undergo great changes, but we must extend the voltages, currents and flux vectors given in equation Eq. (2) such as:

$$[V_s] = \begin{bmatrix} V_{sa} \\ V_{sh} \\ V_{sb} \\ V_{sc} \end{bmatrix}, [I_s] = \begin{bmatrix} I_{sa} \\ I_{sh} \\ I_{sb} \\ I_{sc} \end{bmatrix}, [\Phi_s] = \begin{bmatrix} \Phi_{sa} \\ \Phi_{sh} \\ \Phi_{sb} \\ \Phi_{sc} \end{bmatrix} \quad (10)$$

Thus, the initialisation of the stator resistances, the stator inductances and the mutual inductances matrices are given in Eqs. (2), (4) and (5) respectively by taking into account the introduced fault sections.

The new stator resistances matrix $[R_s]$ is rewritten as follows:

$$[R_s] = R_s \cdot \text{diag}[(1-\mu) \ \mu \ 0 \ 0] \quad (11)$$

Where $\mu = N_{sh}/N_s$ is the relative number of shorted turns.

The stator inductances matrix $[L_{ss}]$ will take the following form:

$$[L_{ss}] = L_{js} \cdot \text{diag} [(1-\mu) \mu 0 0] + L_{ms} \begin{bmatrix} (1-\mu)^2 & \mu(1-\mu) & -\frac{1-\mu}{2} & -\frac{1-\mu}{2} \\ \mu(1-\mu) & \mu^2 & -\frac{\mu}{2} & -\frac{\mu}{2} \\ -\frac{1-\mu}{2} & -\frac{\mu}{2} & 1 & -\frac{1}{2} \\ -\frac{1-\mu}{2} & -\frac{\mu}{2} & -\frac{1}{2} & 1 \end{bmatrix} \quad (12)$$

Therefore, the mutual inductances matrix $[L_{sr}]$ become:

$$[L_{sr}] = [L_{rs}]^T = \begin{bmatrix} L_{ar1} & L_{ar2} & \dots & L_{arn} & 0 \\ L_{shr1} & L_{shr2} & \dots & L_{shrn} & 0 \\ L_{br1} & L_{br2} & \dots & L_{brn} & 0 \\ L_{cr1} & L_{cr2} & \dots & L_{crn} & 0 \end{bmatrix} \quad (13)$$

The rotor resistance and inductances matrixes remain the same as for the healthy case.

4. FIELD ORIENTED CONTROL

The Field Oriented Control (FOC) was developed in order to control the IM speed similarly to the separately excited DC motor. In this method, the flux and torque of the IM can be controlled independently by the stator direct axis current I_{ds} and the quadrature axis current I_{qs} respectively.

In this study, the indirect Field Oriented Control (IFOC) method is used. This choice is appropriate because in this case the flux is not measured or reconstructed but is estimated from the rotor speed [39].

In order to apply the rotor field orientation, the direct flux component Φ_{dr} is aligned in the direction of rotor flux Φ_r , the obtained result is given as follow:

$$\begin{cases} \Phi_{dr} = \Phi_r \\ \Phi_{qr} = 0 \end{cases} \quad (14)$$

The electromagnetic torque in the $d-q$ reference frame is given in the following form [18], [41]:

$$C_e = p \frac{3 M}{2 L_{rc}} (\Phi_{dr} I_{qs} - \Phi_{qr} I_{ds}) \quad (15)$$

Where $M = -(n/2) \cdot M_{sr}$. Under the condition of $\Phi_{qr} = 0$, the IM electromagnetic torque expression becomes:

$$C_e = p \frac{3 M}{2 L_{rc}} \Phi_{dr} I_{qs} = K \cdot \Phi_{dr} I_{qs} \quad (16)$$

In the stator reference frame, the IM flux components take the following form:

$$\begin{cases} \Phi_{ds} = L_{sc} I_{ds} + M \cdot I_{dr} \\ \Phi_{qs} = L_{sc} I_{qs} + M \cdot I_{qr} \\ \Phi_{dr} = M_r I_{ds} + L_{rc} I_{dr} \\ \Phi_{qr} = M_r I_{qs} + L_{rc} I_{qr} \end{cases} \quad (17)$$

By applying the rotor field orientation, the equations of currents components change as follows :

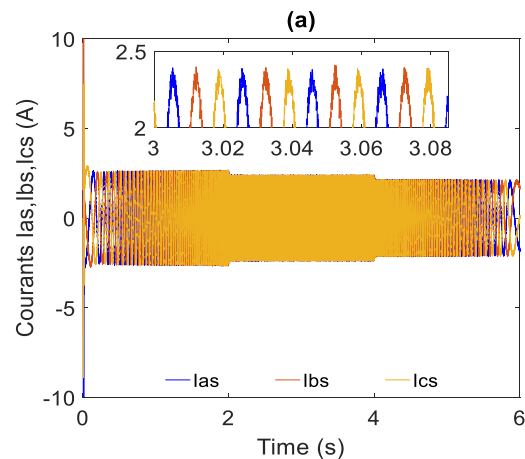
$$\begin{cases} I_{ds} = -\frac{2}{3} \left(\frac{\Phi_{dr} (1 + T_r \cdot S)}{M_{sr}} \right) \\ I_{qs} = \frac{C_e}{K \Phi_{dr}} \end{cases} \quad (18)$$

Where $T_r = L_{rc}/R_r$ is the rotor time constant.

5. SIMULATION RESULTS

In this section, simulation tests of the indirect field oriented control (IFOC) induction motor drive were performed using MATLAB programme software and Fourth Order Runge-Kutta method. For this purpose, a 1.1 kW, 400/230 V, 50 Hz, 4-pole induction motor, with 28 bars on the rotor and 464 turns per phase winding on the stator was used. The parameters of the induction motor are the same as those used in [39].

In order to illustrate the IFOC IM performance under the healthy and faulty conditions, numerical simulation with a reference speed including a run-up (0-1440 rpm), constant speed (1440 rpm) and run-down (1440-0 rpm) is performed, at the start up a torque load of 3.5 Nm is applied.



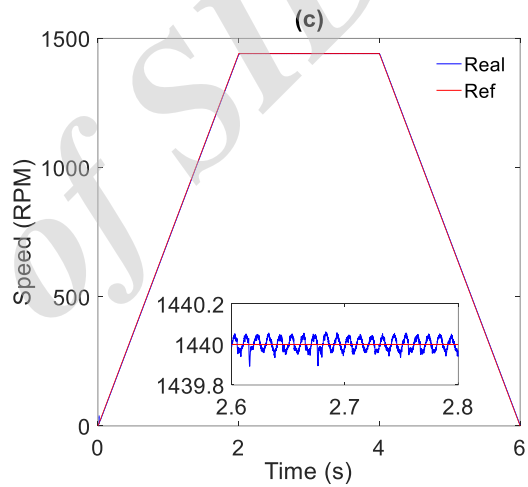
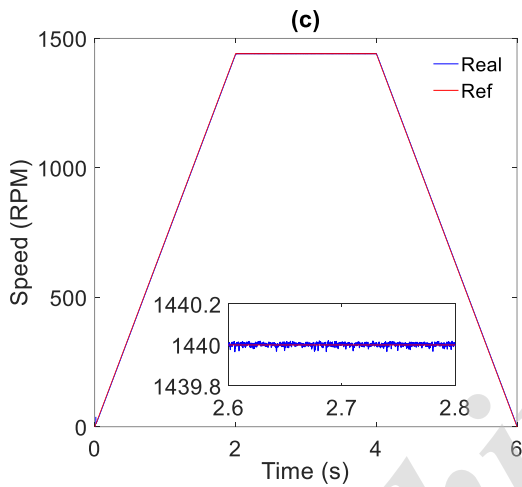
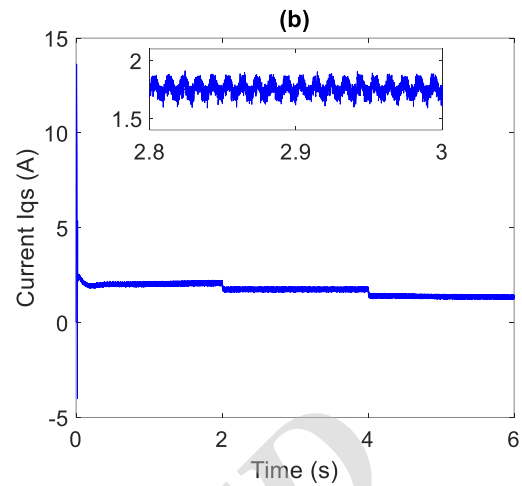
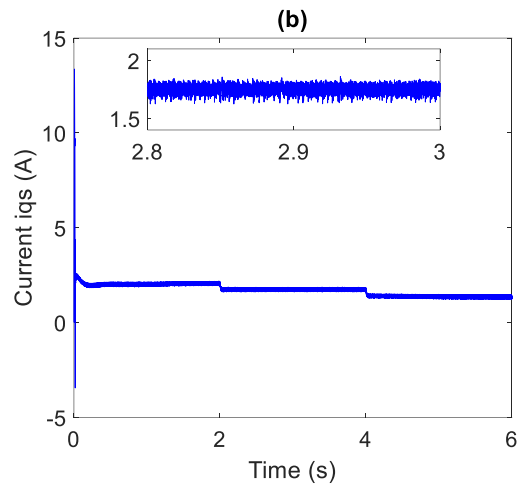
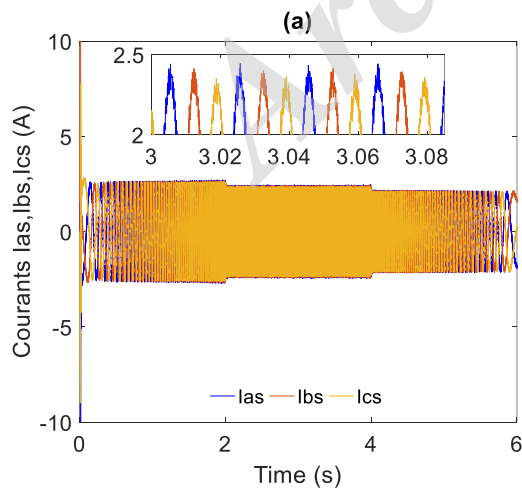


Fig. 2. (a) Stator currents, (b) quadrature current, (c) speed; for a healthy state.

Fig. 3. (a) Stator currents, (b) quadrature current, (c) speed; when 12 stator winding turns are shorted.



The simulation results for the healthy and faulty case are given in Figs. 2 and 3, respectively, where it can be seen that the stator currents and the quadrature current have a very good dynamic; the real speed tracks almost ideally the reference speed.

In addition, by comparing the zooms of the signals present in this two figures, it can be seen that a fault of 12 stator winding turns shorted induce a slight asymmetry between the stator phase currents (Fig.3 a). The faulted phase current amplitude becomes the largest one; this information can be used to localize the stator faulted phase. Otherwise, the presence of oscillations in the quadrature current is noticed (Fig. 3b). Additionally, small fluctuations can be seen in the speed signal (Fig.3c).

6. APPLICATION OF THE FFT TECHNIQUE

In order to explore the frequency spectrum and visualize the impact of the ITSC fault on the stator phase current and quadrature current, the FFT analysis is used.

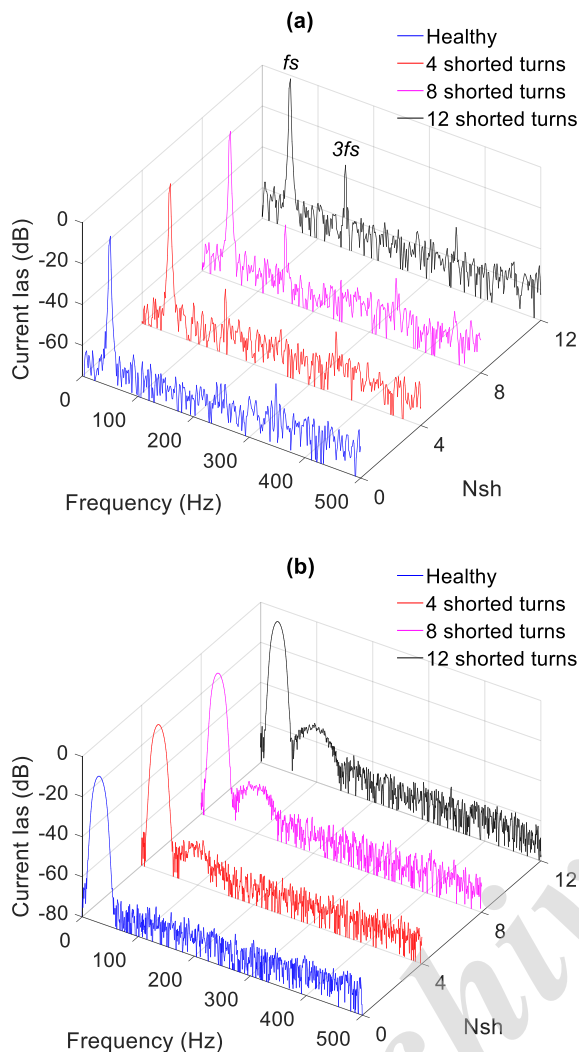


Fig. 4. Stator current spectrums: (a) constant speed operation (50 Hz, 1440 rpm), (b) dynamic conditions.

In Fig. 4a, frequency spectrums of the stator phase current are presented for the IFOC IM operating in constant speed under healthy and ITSC fault (for $N_{sh} = 4, 8$ and 12) of one stator phase. In the healthy case, the stator phase current frequency spectrum includes only the fundamental component frequency f_s . An additional component of $3f_s$ frequency appears in the analysed spectrum when some turns are shorted. The amplitude of this new harmonic component increases with increasing of the N_{sh} level.

On the other side, the FFT technique providing good results for the stationary signals remains inadequate in the case of non-stationary signals, which vary in amplitude and frequency influenced by the rotational speed (as shown in Fig. 4b). Where no fault related

frequency component can be observed in the stator phase current spectrum.

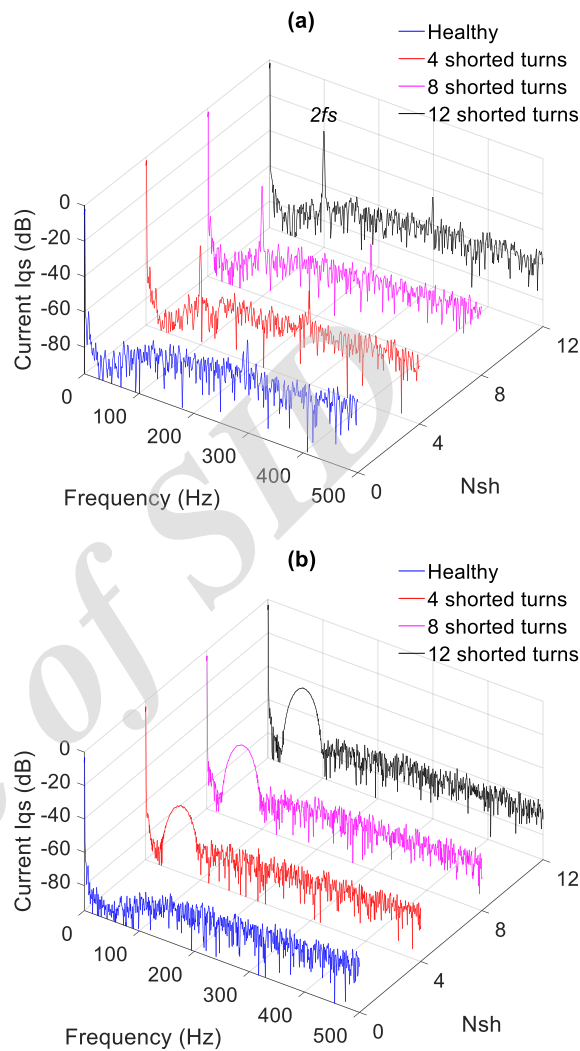


Fig. 5. Quadrature current spectrums: (a) constant speed operation (50 Hz, 1440 rpm), (b) dynamic conditions.

The frequency and order spectra of quadrature current for the IFOC IM operating in constant speed under healthy and ITSC fault (for $N_{sh} = 4, 8$ and 12) of one stator phase are shown in Fig. 5a. Only the constant component f_{dc} is perceptible in the frequency spectrum for the non-damaged motor (Fig. 5a). When the ITSC fault occurs, an additional component of $2f_s$ frequency appears in the analysed spectrum.

As in Fig. 4b, no fault related frequency component can be seen in the quadrature current spectrums given in Fig. 5b.

In order to solve the problem of the non-stationary signals encountered by the FFT analysis, an approach

based on the VKF-OT technique is presented in the following section.

7. APPLICATION OF VOLD-KALMAN FILTER ORDER TRACKING

In this section, performance and efficiency of the proposed diagnosis approach are studied. To this end, a four poles VKF-OT are applied to track and extract the third harmonic component of the stator phase current and the second harmonic component of the quadrature current.

In Fig. 6, the third harmonic component of the stator phase current and its envelope are extracted using the VKF-OT technique. From this figure, it can be clearly observed that the ITSC fault induces an augmentation of the amplitude of the third harmonic component (Fig.6 b, c and d) compared with the healthy condition (Fig.6a). This increase is proportional to the number of short circuited turns N_{sh} . In addition, this increase of amplitude due to the ITSC fault is clearly seen even under the dynamic conditions (run-up and run-down).

The second harmonic component of the quadrature current and its envelope extracted using the VKF-OT are given in Fig.7, where a similar result to those of the third harmonic component of the stator phase current given in Fig.6 can be observed. However, the approach based on the quadrature current is more sensitive and accurate than the stator phase current based approach.

In order to clearly observe the allure of those extracted harmonics during the speed variation, the envelopes of the third harmonic component of the stator phase current and the second harmonic component of the quadrature current during the run-up condition are given in Figs. 8 and 9, respectively.

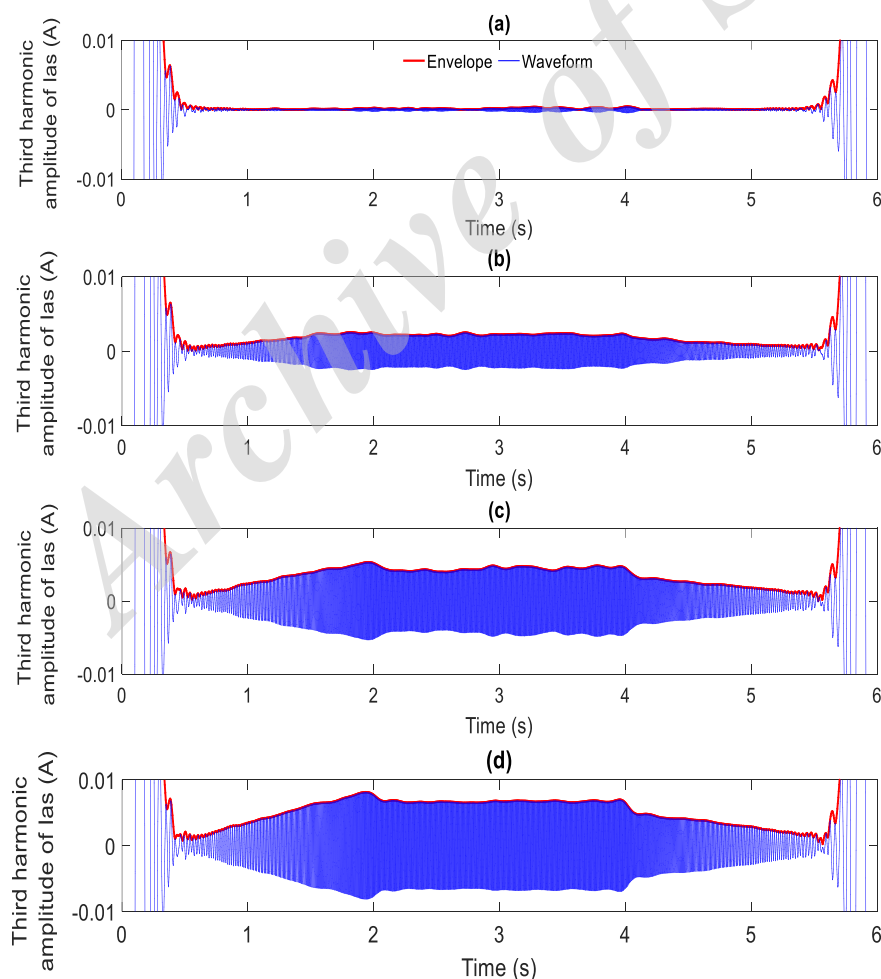


Fig. 6. Third harmonic of the stator current: (a) healthy, (b) 4 shorted turns, (c) 8 shorted turns, (d) 12 shorted turns.

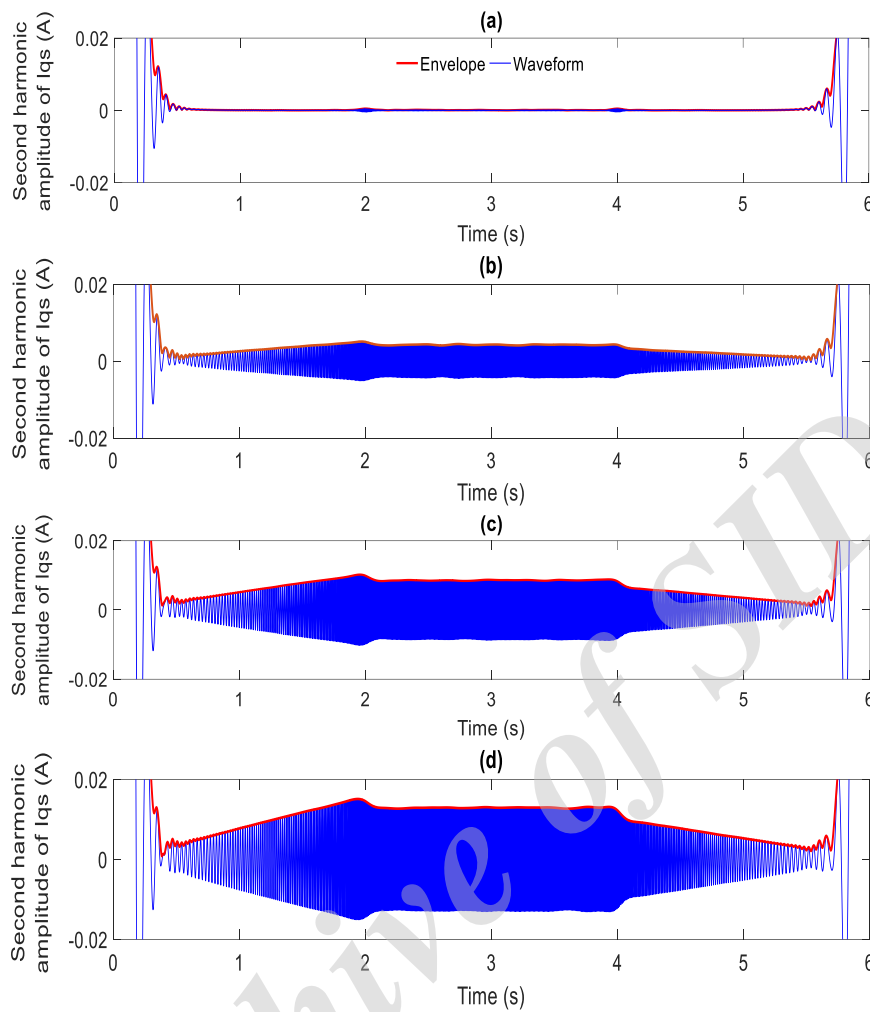


Fig.7. The second harmonic of the quadrature current: (a) healthy, (b) 4 shorted turns, (c) 8 shorted turns, (d) 12 shorted. turns.

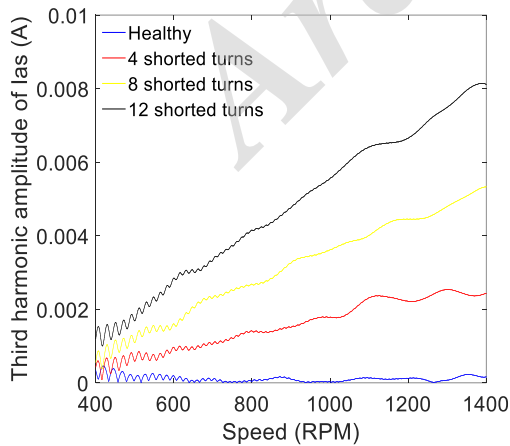


Fig. 8. The envelope of the third harmonic of the stator current under dynamic conditions.

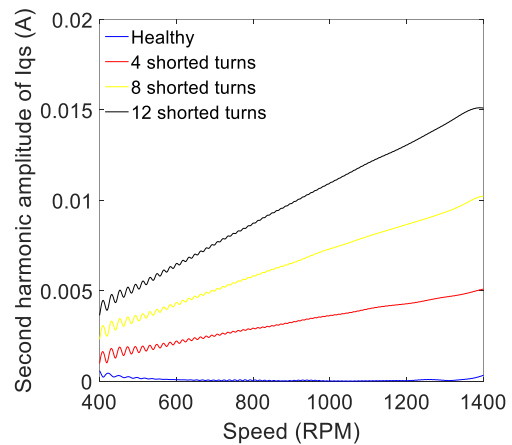


Fig. 9. The envelope of the second harmonic of the quadrature current under dynamic conditions.

As shown in Figs. 8 and 9, the amplitude of the second harmonic component of the quadrature current (Fig. 9) is almost twice greater than the amplitude of the third harmonic component of the stator current (Fig. 8). On the other hand, both harmonics amplitudes are proportional to the rotational speed of the motor and its stator ITSC fault severity.

8. CONCLUSION

In this study a novel approach based on the application of the VKF-OT on the stator phase current and the quadratic current are used in order to track the fault related harmonic components in IFOC IM drive operating under varying speed conditions. The obtained results demonstrate the efficiency of the proposed technique and its ability to overcome the limitations of the FFT technique.

On the other hand, the amplitude of the second harmonic component of the quadratic current significantly changes their value when the ITSC fault occurs comparing to the third harmonic component of the stator phase current. Hence, the use of the quadratic current is the most suitable for the detection of the ITSC fault in its early stage.

One of the great advantages of the proposed approach is that it involves no additional cost, because the current and speed sensors are integral parts of the inverter driven system.

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