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A Survey on Condition Monitoring and Fault Diagnosis in Line-start and Inverter-fed Broken Bar Induction Motors

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Abstract— **In addition to line-start three-phase squirrel-cage induction motors, inverter-fed motors have been also widely employed in various product lines in recent years. The manufacturers and users of the variable speed drive systems are now concerned about the reliable operation of these systems and emphasized to predictive maintenance of the drives. In line-start motors, current signature analysis has been widely used for fault diagnosis. In addition to the mechanical parameters such as speed and noise, other electrical signals including torque, power, and magnetic field have been also considered and their disturbing features upon the characteristics of the above-mentioned quantities have been utilized for fault detection. Keeping in mind that there is much need for further research on the fault diagnosis in the inverter-fed induction motors, an extensive review on this topic is provided in the present article. This review helps to the new comers in the field who arrive to this area with open mind and carry out further research successfully.**

Keywords— Condition monitoring, induction motors, fault dioagnosis, line-start, inverter-fed,review

I. INTRODUCTION

In spite of safe and reliable operation of induction motors, these machines face with several internal and external stresses which cause faults and diminish their performance quality. In case the fault is not diagnosed and cleared, there is a contingency of increasing the fault level, disabling the motor and subsequently losing part of the product line of plants.

Since considerable advances in power electronics devices and industrial drives have been achieved, it is vital to investigate the behavior of the inverter-fed motor variables in healthy and faulty conditions. On contrary to the line-start induction motor, in the inverter-fed case many factors influence the performance of the motor including drive type and its parameters [1, 2]. Different drive types are shown in Fig. 1. In addition to the inherent harmonics, factors such as core saturation, non-sinusoidal distribution of the windings, stator slotting effect and switching harmonics inject more high-order time harmonics to the motor [3]. Some harmonics due to inverter-fed case overlap with the faulty case. Moreover, PWM source causes the disturbance and irregularity which distorts the operation of the motor. Considering the above-mentioned items and undesirable effect of the inverter supplies on the characteristics of the faulty induction motor, it is important to know how different control strategies affect the fault diagnosis principles.

Each type of drive based on its structure, controller type and PWM type technique has its unique effect upon the motor fault diagnosis variables [3, 4].

Some electrical signal monitoring techniques such as MCSA is the most applicable monitoring method due to its high availability, high sensitivity compared to fault and applicability to the motor from far distance in both line-start and inverter-fed cases [5]. The drawback of these methods is their high noise effect on the electrical signals. It is noted that a number of suitable procedures for elimination of the noise has been introduced [6].

In addition to the appropriate monitoring method, accuracy of the fault diagnosis depends on the operating conditions of the motor. In order to precisely diagnose the fault and its level, an exact understanding of the effect of the operating conditions of the motor and drive on the fault indexes is required. In the line-start case, two parameters that have considerable effect on the fault indices are the fault level and the load torque [7, 8]. In the inverter-fed case, there are more dominant parameters including type and bandwidth of controller, drive reference speed and torque values [1-3, 9].

In this paper, line-start and inverter-fed modes are discussed from broken bar fault diagnosis point of view. Section II presents the different aspects of broken bar fault in line-start and inverter-fed induction motors. A comprehensive investigation of different indexes based on their capability of fault diagnosis in different modes is provided. Section III concludes the paper and gives the overall comparison of the fault diagnosis methods in both line-start and inverter-fed cases.

II. COMPARISON OF FAULT PRINCIPLES IN LINE-START AND INVERTER-FED BROKEN BARS INDUCTION MOTORS

Asymmetry arising from the broken rotor bars leads to backward fields which rotate with twice of the slip frequency [1, 10, 11]. The backward fields induce currents in the stator with frequency of $(1\pm 2ks)f_s$, where f_s is the supply frequency, s is the slip and k is an integer.

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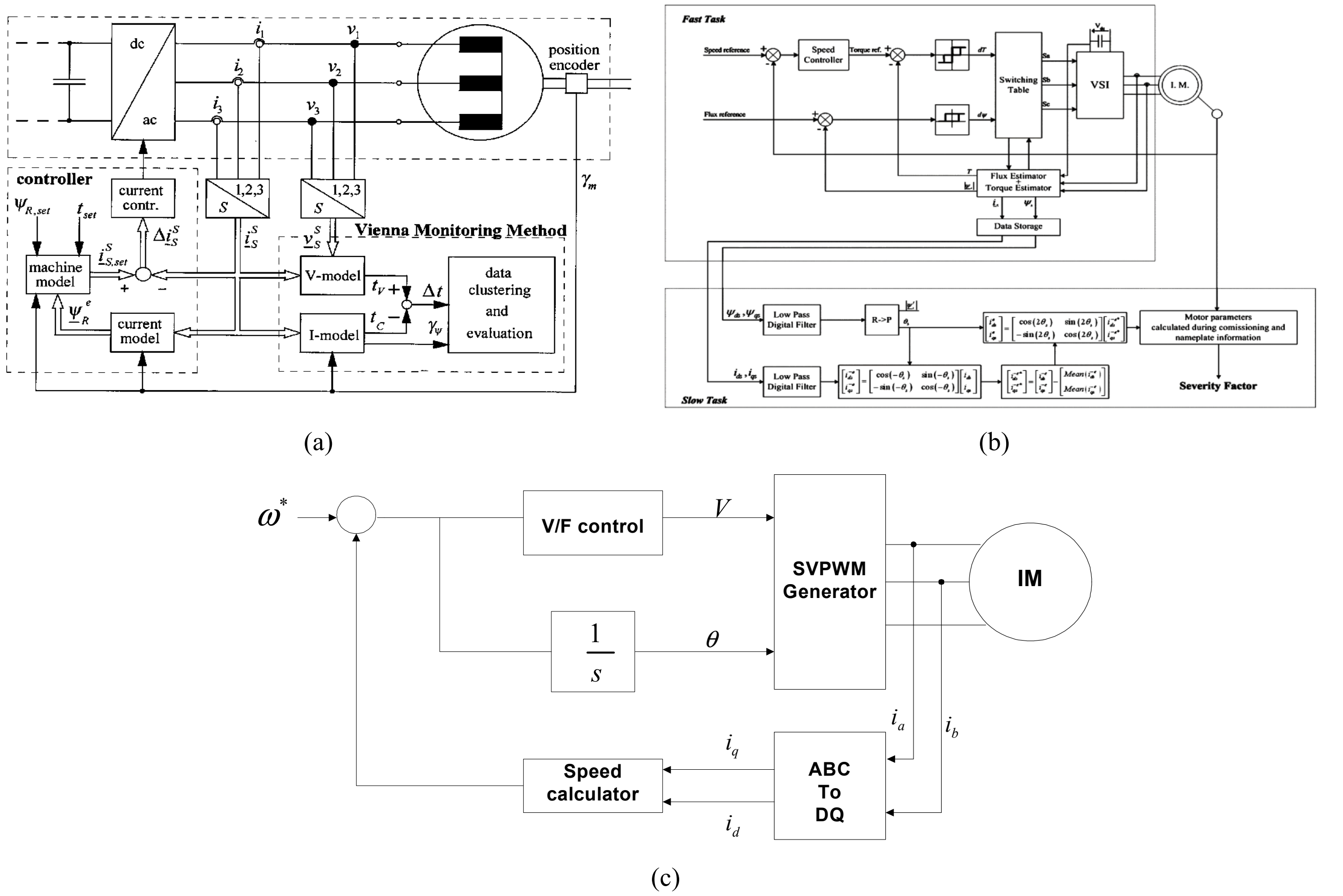


Figure 1. a: Direct torque control b: field oriented control C: Open-loop constant voltage per frequency.

The basis of broken rotor bars diagnosis is extracting the amplitude of these frequencies from the stator steady-state current spectrum [7, 8]. This frequency pattern appears in the form of $f_b = 2ksf_s$ in the torque and speed spectrum. Fig. 1 shows the current and torque spectra in the presence of broken bars [7].

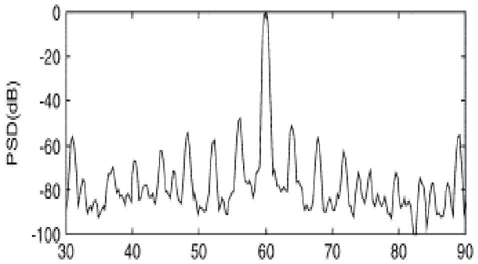
Broken rotor bars result in ripples in the torque and speed of the motor and produce even harmonics [1, 7, 12, 13]. In an inverter-fed motor, the odd harmonics other than 3rd harmonic multiples are injected to the motor. These harmonics induce odd-order harmonics currents in the rotor which subsequently produce odd-order rotor fluxes in the air gap. Therefore, a new frequency pattern in the faulty inverter-fed motor are introduced [14].

where *m* is the supply odd multiples, *n* is the odd multiple harmonics arising from the rotor induced currents and *k* is an integer. In a closed-loop drive, the mutual effect of electrical and mechanical oscillations amplifies each other and amplitude of the above-mentioned frequency spectrum increases [1]. Fig. 2 presents the experimental results of stator current spectrum in the presence of broken bars in line- start and inverter-fed motor [14, 8].

As shown in Fig. 2b, there are more frequencies excited in inverter-fed motor under broken bars fault. These additional frequencies can be calculated by aforementioned pattern. It can be seen that there is little shift in frequency spectrum in the faulty motor with respect to the healthy one in inverter-fed case. Applying feed-back, the oscillations of the load caused by fault appear in the motor voltages and consequently the average of electromagnetic torque reduces more than that of the line-start case. So slip varies.

The presence of more harmonics arises from saturation due to the broken bars which increases the torque ripples and reduce the mean torque [1, 7]. Generally, more distributed broken bars around the rotor can reduce the local saturation effects which lead to lower sidebands harmonic amplitude [12]. The sidebands amplitude increase by increasing the load [7, 8].

In the transient mode, amplitudes of sideband components do not depend so much on the load and its oscillations. Therefore, study of the transient mode of the motor is an appropriate procedure in the broken bar fault diagnosis [7, 15]. Since the sideband components are close to the supply harmonics and use of low-pass filters in the drive-controlled motors creates overlapping between the components and supply frequencies, this makes very difficult to diagnose the sideband component amplitude in the inverter-fed motor. Therefore, alternative indexes have been presented for broken bars fault. Virtual current technique may be used for broken rotor bars [2], in which analytical method has been proposed and then simulation and experimental results have been compared. The basis of the method is evaluation of the oscillations amplitude of the harmonic $2sf_s$ of the rotor flux and



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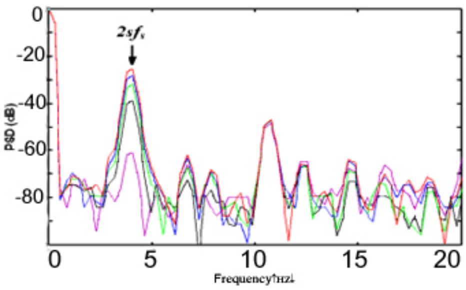
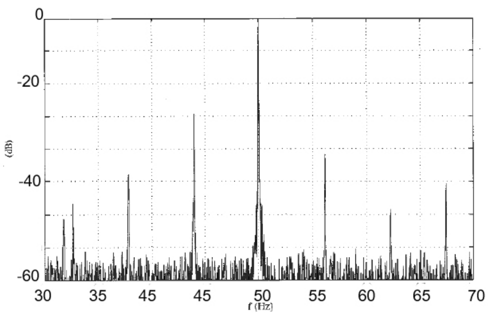


(b)

Figure 2. a: Current spectra of motor with broken bars. b: torque spectra of motor with broken bars [7].



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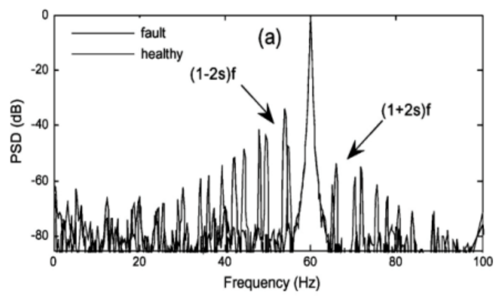

(b)

Figure 3. Current spectra of motor with broken bars in a: line-start. b: inverter-fed [8].

obtaining the virtual current generates this flux in a broken bar motor with field oriented drive. The broken bar can be considered as an extra resistance in one of the phases (Fig.3 [2]). In this paper, voltage model of two phases of the motor has been utilized and *dq* voltages of the faulty motor have been expressed as a function of the currents.

The inductances have been estimated by winding function method (WFM) [1] and substituted in the real model of the motor. Advantages of this modeling method are that the motor variables are available as *dq* components. Also some components of the motor variables have relatively unique behavior against the fault, so those components are achieved. Meanwhile, use of the input speed reference frame is an appropriate idea for eliminating the fundamental harmonics and preserving harmonics arising from the fault.

In the ideal case, the bandwidth of the controller is very large compared to the slip frequency and decoupling between the d and q have been done well, so oscillations merely due to the motor current will appear and motor flux will have constant value.

In practice, the controller bandwidth is small and oscillation error in the flux will be observed. The simulation results in [2] has diagnosed the number of the broken bars precisely and index amplitude is almost independent of the load level, drive reference speed and controller bandwidth (Table I)

Of course, some overestimation is observed by increasing the load in experimental results [2]. Experimental results based on this method show that this method is not practically useful, because the index used has been obtained based on many assumptions including constant magnetizing inductance, fixed motor time constant and neglecting inner currents of the bars (due to weakness of the insulation). The error of this method rises by increasing the load; the reason is increase of the rotor demagnetizing feature due to the inner currents of the bars. Virtual current technique (VCT) in the tuned drive circuit is applicable. VCT needs knowledge of the transfer function of current control loop. Some have used current model of two-phase motor for broken rotor bars fault. In the current model, fluxes are expressed as a function of the current. In [9, 16], the torques of current and voltage models under FOC control are evaluated and index of the broken bars have been defined as the ratio of difference of these two torques and mean torque of the voltage model. This method is called the Vienna monitoring method (VMM). In the healthy motor, the values of two torques are identical. In the faulty motor, torque value of the voltage model differs with that of the current model. VMM is not so sensitive against load variations and controller reference speed. However, two types of motor models are required and index variations versus variations of the controller bandwidth have not been investigated. VMM is a model-base method and therefore the model varies by change of the motor parameters such as raising the resistance with the temperature rise.

Injection of high frequency signal to the motor is an alternative method for broken rotor bars in both line-start and inverter-fed motors [17]. An appropriate index is obtained by applying the high frequency and low amplitude voltage to the motor and estimating high frequency negative sequence current. This index is almost independent of the operating conditions. This method is applicable in any type of drive. The advantage of the negative sequence current is its independency of the temperature variations. Load fluctuations has low effect upon current i_d, however i_d depend highly on the *d-axes* flux. Due to the presence of $2sf_s$ harmonics in the motor current arising from the broken rotor bars fault and taking apart the state equations of the motor as components, the harmonics due

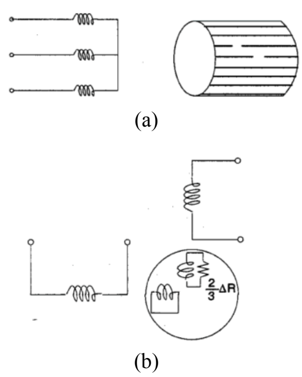

Figure 4. Rotor bar breakage a: three-phase equivalent b: two-phase equivalent [2].

to the fault appear in the synchronous reference frame as $2sf_s$ in i_d and i_q spectra. Variations of the amplitude of i_d and i_q versus fault level and variations of proportional coefficient of *PI* controller in a field oriented drive has been investigated. Fig. 5 shows the index variation. By increasing k_p in the spectra of these currents, frequency displacement is generated and also amplitude of i_q spectrum varies. Since amplitude of i_q varies by load fluctuation and k_p changes, it may not be a suitable index for fault diagnosis. Amplitude of i_d is an appropriate method for fault diagnosis in the inverter-fed motor; however, a regular relationship between the fault level and amplitude of this signal has not been so far proposed.

Pendulous oscillation is a fantasy index in the broken rotor bars diagnosis [18]. In the evaluation of this index a filter has been used; it is also applicable to the inverter-fed motors. By raising the load, amplitude of the pendulous oscillations index in the line-start and open-loop PWM cases increase and in the closed-loop PWM decreases. Some AI-based methods are able to diagnose broken bar even partial broken bar [5]. These methods need a time consuming statistic computations that is not suitable in industry. Due to irregular variations of signals of the motor transient mode in the inverter-fed case, fault diagnosis in these motors are carried out through the analysis of the steady-state signals. In [7], appropriate indexes have been obtained from line-start motor transient mode signals. Another group of indexes that present the severity of fault at time-frequency domain are those which are obtained by Hilbert-Huang transform [19, 20]. These indexes have the advantage of considering both the time and frequency fluctuations simultaneously.

CONCLUSION

A comprehensive and complete review of three-phase squirrel-cage induction motors fault diagnosis has been presented and fault detection methods in two line-start and inverter-fed cases have been compared. It was shown that the dominant parameters on the fault diagnosis in the inverter-fed motor are more than that of the line-start case. The drive controller coefficients, reference speed and torque, controller bandwidth and load of the motor are the influential factors on the amplitude of the any proposed indexes.

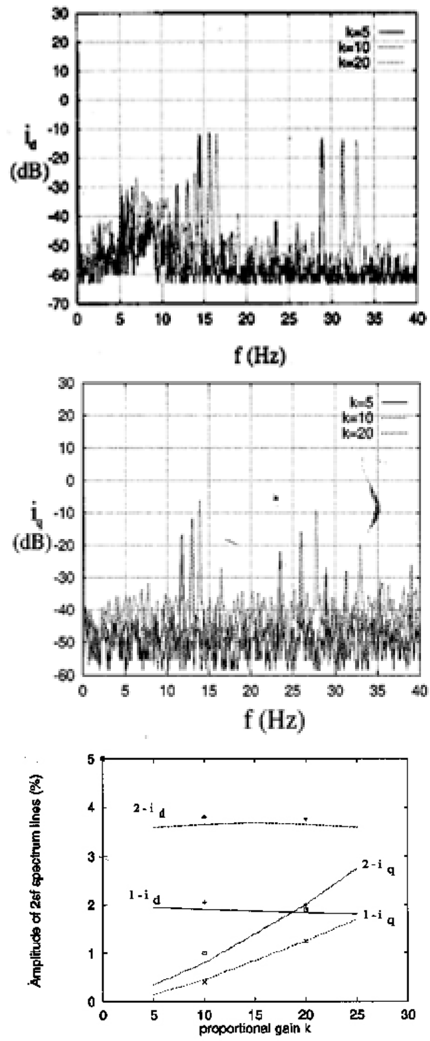

Figure 5. Stator current coefficients spectrum of motor with healthy and broken rotor bars. [14] Up: i_d versus k_p Middle: i_q versus k_p Bottom: i_d , i_q versus k_p and different number of broken bars

In any feeding type, the stator current signal is recommended as the most appropriate signal for monitoring the operating conditions of the motor. Of course, in the inverter-fed motor, some components of the signal are used for fault diagnosis. A combination of two voltage and current signals of the motor can be suggested as an appropriate procedure for fault diagnosis in the inverter-fed motor. In all introduced indexes for inverter-fed motors steady-state signals of the motor are employed. In spite of this, in the line-start motor appropriate indexes using transient mode signals have been presented.

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TABLE I. SIMULATION RESULTS OF A MOTOR UNDER FOC DRIVE WITH BROKEN BARS [2]

Number of broken bars	Measured/calculated values				
	$2\Delta\psi_{dr}$ (Wb)	$\Delta\psi_{drf}$ (Wb)	Δi_{dsf} (A)	$\bar{i}_{qs}$ (A)	n_F
1	0.0116	0.0218	0.4518	16.01	**0.80**
2	0.0267	0.0484	1.0408	16.05	**1.87**

Load torque (% rated torque)	Measured/calculated values				
	$2\Delta\psi_{dr}$ (Wb)	$\Delta\psi_{drf}$ (Wb)	Δi_{dsf} (A)	$\bar{i}_{qs}$ (A)	n_F
25	0.0264	0.0397	0.3235	5.30	**1.76**
75	0.0267	0.0484	1.0408	16.05	**1.87**

Reference speed (rpm)	Measured/calculated values				
	$2\Delta\psi_{dr}$ (Wb)	$\Delta\psi_{drf}$ (Wb)	Δi_{dsf} (A)	$\bar{i}_{qs}$ (A)	n_F
500	0.0272	0.0493	1.0603	16.06	**1.91**
1450	0.0267	0.0484	1.0408	16.05	**1.87**

Flux loop bandwidth (Hz)	Measured/calculated values				
	$2\Delta\psi_{dr}$ (Wb)	$\Delta\psi_{drf}$ (Wb)	Δi_{dsf} (A)	$\bar{i}_{qs}$ (A)	n_F
1.0	0.0975	0.0515	1.1067	16.09	**1.99**
2.7	0.0739	0.0504	1.0830	16.06	**1.95**
10.0	0.0267	0.0484	1.0408	16.05	**1.87**

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