

Advancement of Fault Diagnosis and Detection Process in the Industrial Machine Environment

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Abstract. Machine fault diagnosis is a very important topic in industrial systems and deserves further consideration in view of the growing complexity and performance requirements of modern machinery. Currently, manufacturing companies and researchers are making a great attempt to implement efficient fault diagnosis tools. The signal processing is a key step for the machine condition monitoring in complex industrial rotating electrical machines. A number of signal processing techniques have been reported from last two decades conventionally and effectively applied on different rotating machines. Induction motor is the one of widely used in various industrial applications due to small size, low cost and operation with existing power supply. Faults and failure of the induction machine in industry can be the cause of loss of throughput and significant financial losses. As compared with the other faults with the broken rotor bar, it has significant importance because of severity which leads to a serious breakdown of motor. Detection of rotor failure has become significant fault but difficult task in machine fault diagnosis. The aim of this paper is indented to summarizes the fault diagnosis techniques with the purpose of the broken rotor bar fault detection.

Keywords: machine fault diagnosis, signal processing technique, induction motor, condition monitoring.

1 Introduction

Machine fault diagnosis and condition monitoring are very important in industrial engineering system, and it needs more attention considering increasing the performance needs of modern machinery. Machine fault and failure will have quality implications and sometimes may cause of shutdown of machinery and many financial losses. Therefore, it is necessary to develop intelligent diagnosis systems that will be helpful to provide a reliable and accurate diagnosis which can be able to provide accurate information regarding the present machine condition [1].

Induction machine (IM), which is also called the asynchronous motor, is a critical component of mostly industrial machinery system which is widely using in the petrochemical, transportation, manufacturing and power systems just because of its simplicity, reliability, high excess power load [2]. IM consist of a magnetic circuit connected with the two electrical circuits which rotate to each other. Compared with the Direct Current (DC) motors, IM is low cost, less rugged configuration, in small size, less maintenance and can operate on the accessible power line [3]. The range size of induction motors is from

tiny to over 104 hp. But, in the practical applications, IM is subjected to inescapable electrical, mechanical and thermal stresses and become the cause of different faults [4]. Sometimes these faults may cause of shutdown of machinery and many financial losses [5]. An efficient diagnosis technique can reduce the unscheduled maintenance cost and trace the fault at early development stages. Basically, IM was invented by N. Tesla [6]. The rotating parts of IM do not need the linking electricity due to the energy which is provided by the electromagnetic induction [7]. The stator can generate a rotating magnetic field which induces a substituting electromagnetic energy and power current in rotor. This inferred power current in rotor and the rotating field in stator are communicated to each other and induce a motor torque [8].

2 Literature Review

Numerous methods of induction motor fault diagnosis were developed in the last decades and many techniques have been proposed [9, 10]. The most common approach is the motor current signature analysis (MCSA) [11]. Several of induction motor faults detection and identification techniques are based on Fast Fourier Transform

spectral signature analysis [12–14]. Other techniques include vibration analysis, temperature measurements, harmonic analysis of speed fluctuations [15, 16], vibration monitoring [17], state and parameters estimation [18], either axial flux or air-gap torque analysis [19], acoustic noise measurement, and magnetic field analysis [20–23]. Currently, more and more new techniques based on artificial intelligence (AI) have been utilized for diagnostic induction motor faults, such as fuzzy logic [24, 25], genetic algorithms [26], neural network [27], Bayesian classifiers [28], and envelope of the three-phase stator current with AI-based on Gaussian mixture models and reconstructed phase spaces (RPSs) [29].

The methods used to diagnose broken bars can be broadly categorized into two types, invasive and non-invasive fault diagnosis techniques [30]. The invasive methods diagnose broken bars by monitoring the deviation of the magnetic potential vector and asymmetrical magnetic flux distribution, gyration radius, asymmetrical magnetic flux distribution, torque and speed fluctuation and so on [31]. In these methods, sensors and costly measurement equipment's are needed, which will increase the complexity and expense of the diagnostic method [32]. Induction motor faults often generate particular frequency components in the current spectrum. The abnormal harmonics contain potential information of motor faults. Therefore, the frequency analysis approach is the most commonly used method to diagnose induction motor faults. The aim of this paper is indented to investigate a broad list of references to the recent advancement and summarizes the fault diagnosis techniques with the purpose of BRB fault detection.

3 Research Methodology

3.1 Rotor structure in induction motor

In Induction motor, there are two types of rotor, i. e. Squirrel cage and wound rotor. Squirrel Cage Rotor (SCR) is a very simple and widely used rotor for IM manufacturing. SCR is consists of the plastic-coated iron core and it is slotted around its circuit lengthwise. Solid aluminium or copper bars are firmly embedded or pressed into rotor slots [33]. Short-Circuiting rings are embedded or welded to the bars at both edges of rotor. Short-

Circuiting bars don't have to be particularly insulated from the core just because of resistance which is below the core [34]. For the placement of rotor core, in some kind of rotors, the end rings and bars are cast as a single cage component. The short-circuiting components are induced in the shorted turns by the stator flux. As compared with the wound rotor with the SCR, the SCR is comparatively simple and easy to fabricate [35].

Under average operating situations, great thermal and mechanical stresses are presents when the machine is being constantly restarted and with heavily loaded [36]. It is well known that the rotor current during starting can be increased ten times the normal full load current and can be the cause of large stresses in the rotor circuit. The bar cracks have increased the resistance and produced the heat at the crack. The crack bar will almost break, and arcing will happen across the break. This arcing will then damage the laminations around the faulted bar. The nearest bar will carry an increased current and lead to increase the current and could do damage the stator winding and rest of rotor bars as well [37, 38].

By applying the threshold rules to diagnose the BRB fault in healthy induction motors, the following authors in Table (1) proposed the different estimation practical models in [15–17]. These models are used by the other researchers in [16] which put aside usage of proposed models for the BRB fault detection in various practical applications such as compressors, fan, pumps, etc.

Generally, Benbouzid and Thomson present in their papers an insignificantly higher estimation the number of rotor broken bars based on the almost similar results as shown in Figure 1. The intensity of both sideband (left and right) based on the different load conditions of IM. Some of the similarity between Benbouzid and Thomson models results shows similarity between the lower values of LSB magnitude values i.e. 5-8 dB. Shaft load should always be in good condition during experiment but it's difficult to maintain in practice to precisely nominal load on an investigated IM. The main disadvantage of the discussed models is the relationship with IM slide necessary to calculate sidebands frequencies, and IM frequency slip which is consist of intensity, experimental load conditions and fluctuation of the load between diffident motors were not presented in proper way.

Table 1 – Broken bar detection experimental results* [10–12]

Author	BRB models	The amplitude at left side band (LSB)			
		50.91 dB	27.51 dB	30.06 dB	40.16 dB
Benbouzid [10]	$\frac{I_{BRB}}{I} = \frac{\sin \alpha}{2p(2\pi - \alpha)}$	0.39	4.00	3.45	3.39
Bellini [11]	$\frac{I_{BRB}}{I} = \frac{n}{N}$	0.09	2.04	1.58	1.57
Thomson [12]	$\frac{I_{BRB}}{I} = \frac{n}{2N - np}$	0.18	2.10	2.88	2.86

* where $\alpha = 2\pi pn/N$; I_{BRB} – amplitude of the LSB; I – basic supply current; N – number of rotor bars; n – number of broken bars; p – number of pole pairs.

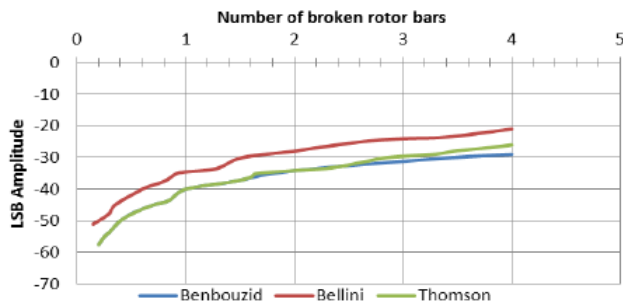


Figure 1 – Comparison of broken bar models

3.2 Common rotor related faults

Rotor related faults are generally related to magnetic stresses from electromagnetic forces, thermal stresses, residual stresses in unsatisfactory mechanized and some environmental stresses that are caused by moisture [39]. Various stresses are comprehensively has been described in [40]. Rotor related faults are normally starting at server resistance and produce the high temperature, and then lead to the damage the rotor bar [41]. This fault normally takes place at end rings of cage. For the detection of BRB fault, most of important parameters are needed to observe in which vibration, variation in speed, motor current signature, and air-gap flux are significant parameters. Rotor related failure into IM can be categorized into breakage of rotor bars, rotor eccentricity, and breakage of end-rings. The following section concisely describes the abovementioned faults in rotor [42].

The rotor bar breakage is the key fault in the rotor of IM. Breakage of rotor bars does not normally result in an instant failure of the IM and can cause increased heating, loss of torque and stressing the neighboring bars [43]. During the operational mode of IM, the rotor bars can be fractionally and completely cracked due to the stresses. Breakage of rotor bars does not normally result in an instant failure of the IM. Broken bars can cause a loss of torque and increased heating and stressing of nearby bars [44]. Being able to identify the broken or cracked bars early decreases shutdown time and lowers repair expenses since the repairs are generally only for the rotor. If the bars are not repaired and the motor continues to operate, additional bar breakage is likely as well as damage to other components in the motor [45]. The more rotor bars that break, the larger the loss of torque and the higher the current in adjacent bars. The higher current causes higher temperatures in the area near the broken bars and will also cause stator damage due to excessive heat. Oscillations in speed and torque are indications breakage of rotor bars, which can cause increased wear of other motor components. Hafezi et al [46] presented the distinctive reasons for the BRB failure used by the prediction based model using the instantaneous angular speed (IAS) analysis to simulate the IM performance in healthy and in breakage rotor bar condition. To observe the behavior of IM, Runge Kutta Integration (RKI) algorithm was applied to resolve the rotor bar failure problem.

Eccentricity related faults in rotor cause a consistent air gap that corresponding the unbalanced magnetic force and non-consistent air gap magnetic field which producing the vibration and noise on stator [47–49]. Most of the research [50–54] has been published in last years about the vibration and noise on Permanent magnet synchronous (PMS) and DC motors but little research has been done on the eccentricity related fault in rotor to observe the vibroacoustic behavior of IM motors. In ideal operating motor [55], basically the rotor is centrally lined up with the stator and rotation of the rotor's center is similar to the stator geometric center. A rotor eccentricity can take place in both static and dynamic eccentricity conditions. In static eccentricity condition, the position is fixed for the minimal radial rotor air-gap length in space [56].

4 Results

4.1 Fault diagnosis techniques for BRB

When any fault happens, some of the machine parameters have to be changed. These parameter changes depend upon the severity of the fault and interaction with other parameters. A broad range of survey [34–44] has been done from different researchers and many techniques (e. g. thermal monitoring [50, 51], current analysis [47, 48], torque monitoring [54, 55], noise monitoring [52, 53] and vibration analysis [49]) for fault detections has been investigated, but all other techniques except MCSA are required some expensive sensors for monitoring machine condition [20, 45]. This is the reason the current monitoring techniques is non-intrusive and also may use for the remote monitoring in the central motor control center. Several IM Faults diagnoses techniques are based on the Fast Fourier Transform (FFT) spectrum signature analysis using the stator current [47]. The methods used to detect the BRB fault in IM can be classified into two categories, invasive and non-invasive method [56]. The conventional static relay and electromechanically diagnosis techniques in the industries are based on the invasive method because of insertion of temperature sensor in IM which is used to the measure temperature impact significant on degree of protection. On the other hand, non-invasive method is more using and preferable technique in the industries these days because of inexpensive and easily accessible measurement to observe the machine healthy and abnormal conditions without separation of IM from system [57].

4.2 Motor current signature analysis

Motor current signature analysis (MCSA) is novel methods for diagnosing the BRB fault in IM due to its low cost and simplicity. Basically, this method is based on the produced sidebands around the fundamental supply frequency in stator current [57]. Several works [58–60] has been reported in previously published papers for the development of machine condition monitoring application using MCSA among different industrial case studies [47]. The MCSA use the current spec-

trum of machine for finding the required attributes of fault frequencies at what time a fault present. Literature shows in [58–60] that the critical point about MCSA is sensing electrical signal which has current sensing mechanism that can detect the broken rotor bar, shorted turn, and airgap eccentricity faults, etc. at early stages of fault development and avoid the severe damage or completely shutdown of machine. The classification of different available diagnosis techniques for BRB as follows in Figure (2).

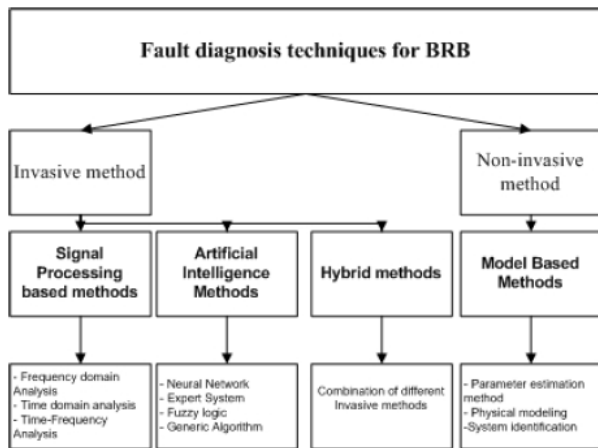


Figure 2 – Fault diagnosis techniques for BRB fault

Ahmed et al in [61] presents an online machine fault system which senses the current without any user interpretation at unspecified load. A frequency filter applied which contain frequency characteristic of induction machine of normal load condition using a set of some expert system. All these generated frequencies managed through a table and neural networks clustering algorithm inputs compare with the initial machine performance characterizes. While training the system, it only requires the good condition of the machine. Since a fault is going to present and demean the current signature while it progresses in excess of time, the system compares these changes with the originally learned spectra which are stored in table, and if some change in the spectra, it indicates the fault condition and generates an alarm. The Author’s claimed that the combination of rule-based expert system frequency filter and neural network clustering algorithm increase the system’s capability to detect the machine faults with small spectral changes.

In [62], Ayhan et al. stated that MCSA utilized the outcomes of spectral analysis of stator current. Noise and distortion always become a cause of disturbing the signal and effecting on the procedure of detection faults at early stages. The research work shows that using Fast Fourier Transform (FFT), the frequency signature spectrum of some asymmetrical machine faults including broken bar, rotor asymmetry, bearing failure, etc. can be easily identified which leads to better understanding of motor current spectra. Supangat concludes in another paper [63] is that FFT technique is useful for many application those are using in machine fault de-

tection where signal is stationary. But this is not good for the analysis of those signal in which frequency get some variation and non-stationary signals. This issue can be resolved through time-frequency techniques. i.e. Short Time Fourier Transform (STFT).

4.3 Spectral feature selection and fault characteristics

One of the important tasks in BRB fault diagnosis process is to analyze the spectrum and selection of sensitive frequency features. Hence, there is a need to identify and select the most valuable features which are very important in machine fault identification and localization process. To use the complete set of feature sets will cause much cost of time and low performance because in the original features set there are numerous irrelevant and laid off features existed [47].

The frequency characterizations of different fault condition models have been illustrated from previous literature on current signature analysis. We aim to use these frequencies models in a further phase of our research to identify the fault frequencies from current spectrum. Faults in electrical machine produce characteristic fault frequencies that could be examined by using spectrum analysis of one or more sensor quantities such as current. The current can be used to compute the instantaneous power. The following Table 2 shows some typical faults conditions and the frequency components indicators of abnormality.

Table 2 – Typical faults and associated frequencies* [40–42]

Fault	Frequency characteristics, Hz
Broken rotor bar (BRB)	$f_{brb} = f_1(1 \pm 2s)$
Air gap eccentricity	$f_{ecc} = f_1[(1 - s)R/p \pm k]$
Shorted turn fault frequency	$f_{st} = f_1[(1 - s)n/p \pm k]$

* where f_1 – supply frequency; s – per unit slip; R – number of rotors; p – number of poles-pairs; k, n – harmonic number; $n = 1, 2, 3, \dots$

4.4 Signal processing techniques for brb fault detection

Most of the successful machine fault diagnosis and condition monitoring tools depend on different signal processing techniques. Through signal analysis, it is possible to decide the healthy and faulty frequencies of various machine components in time and frequency domain. The severity of the fault can be measure through amplitude of signal both in time and frequency domain. Fast Fourier transform (FFT) is very simple, fast and easy to apply on current spectrum signal in frequency domain but the main problem with FFT is that not appropriate for the transient signal [50]. But this problem is not significant in that condition when the signal is stationary.

To overcome this deficiency, the Short-Time Fourier Transform (STFT) can be used for analyzing the non-stationary and transient signal in the time-frequency domain. But the main problem with this technique is that it can be analyzed the signal for all frequencies with a set sized of window [51].

STFT is also presented the poor frequency resolution. These two problems of STFT can be overcome by applying the wavelet transform which provides the

flexible extended time interval and better frequency resolution. A detailed comparison of the different signal processing methods is illustrated in Table 3.

Table 3 – Comparison between different signal processing techniques

Technique	Faults diagnosed	Advantages	Disadvantages
FFT [66]	<ul style="list-style-type: none"> • broken rotor bar fault • short winding fault • air gap eccentricity • bearing faults 	<ul style="list-style-type: none"> • suitable for high load conditions • easy to implement • good for visualization fault symptoms 	<ul style="list-style-type: none"> • lost time information • not effective in light load condition
STFT [67]	<ul style="list-style-type: none"> • broken rotor bar fault • bearing faults 	<ul style="list-style-type: none"> • fast speed • suitable for varying load conditions 	<ul style="list-style-type: none"> • analyze signal with a fixed-sized window • poor frequency resolution
Wavelet transform [68, 69]	<ul style="list-style-type: none"> • broken rotor bar fault • short winding fault • bearing faults • load fault 	<ul style="list-style-type: none"> • fast speed • suitable for varying load and light load conditions • excellent low time and frequency resolution for low-frequency sideband components 	<ul style="list-style-type: none"> • absence of phase information for a complex-valued signal • poor directionality • shift sensitive for input-signal causes an unpredictable change in transform coefficients in time

5 Conclusions

This paper presents a comprehensive comparison review on a broad list of references to the recent advancement and summarizes the fault diagnosis techniques with the purpose of BRB fault detection.

A comprehensive attempted based on the recent references is summarized and development in the field of

machine condition monitoring and fault diagnosis. It is anticipated that this research will be very helpful for those who are concerned with understanding the dominant capability of machine condition monitoring and fault diagnosis. The chosen reference list is intended to cover all possible significant area in machine condition monitoring and published in recent years.

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Удосконалення процесу діагностування несправностей у промислових умовах

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Анотація. Діагностика несправностей машин є дуже важливою проблемою у промислових системах і за-
слуговує на подальший розгляд з огляду на зростаючі вимоги до складності та підвищення експлуатаційних
характеристик сучасних машин. У даний час виробничі компанії та дослідники роблять значні спроби впро-
вадити ефективні засоби діагностики несправностей. Оброблення сигналів є ключовим кроком у моніторингу
стану машини в складних промислових електричних роторних машинах. За останні роки було розроблено ряд
методів оброблення сигналів, які традиційно застосовуються у різних роторних машинах. Зокрема, індукційні
двигуни є широко уживаними в різних галузях промисловості завдяки їх невеликим розмірам, низькі собівар-
тості та роботі з існуючим джерелом живлення. Несправності індукційної машини можуть стати причиною
значних промислових і фінансових втрат на підприємстві. Порівнюючи різні несправності, можна зробити
висновок, що діагностування дефектів валу має важливе значення через складність наслідків цього дефекту,
що призводить до серйозної несправності двигуна. При цьому виявлення цієї несправності є надскладною
проблемою технічної діагностики несправностей машини. Тому метою цієї роботи є узагальнення методів те-
хнічного діагностування несправностей машин для виявлення дефектів валу.

Keywords: діагностування несправностей машини, методика оброблення сигналу, індукційний двигун, моні-
торинг стану.