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Research article

A review and comparison of fault detection and diagnosis methods for squirrel-cage induction motors: State of the art

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ABSTRACT

Preventing induction motors (IMs) from failure and shutdown is important to maintain functionality of many critical loads in industry and commerce. This paper provides a comprehensive review of fault detection and diagnosis (FDD) methods targeting all the four major types of faults in IMs. Popular FDD methods published up to 2010 are briefly introduced, while the focus of the review is laid on the state-of-the-art FDD techniques after 2010, i.e. in 2011–2015 and some in 2016. Different FDD methods are introduced and classified into four categories depending on their application domains, instead of on fault types like in many other reviews, to better reveal hidden connections and similarities of different FDD methods. Detailed comparisons of the reviewed papers after 2010 are given in tables for fast referring. Finally, a dedicated discussion session is provided, which presents recent developments, trends and remaining difficulties regarding to FDD of IMs, to inspire novel research ideas and new research possibilities.

1. Introduction

Induction motors (IMs) are popularly integrated in equipment and used in many manufacturing processes, industrial applications and facilities. It is important to maintain the health of IMs to keep many industries running well. However, various faults frequently happen in IMs due to tough working conditions, regular wear and tear, enduring and/or overrated loads, unexpected events and many others. Thus, FDD is necessary to avoid catastrophic failures, shutdown, associated repair and operational costs, and unsafe operation of IMs.

In the literature, several recent reviews are available for FDD of IMs. In [1] and [2], FDD methods dedicated for medium-voltage IMs and for stator winding faults are reviewed, respectively. However, these two reviews do not include methods after 2010. On the other hand, comprehensive reviews of FDD for overall motor drive systems which include various electric machines, power electronics and drives are provided in [3] and [4]. However, no detailed comparison or discussion is given beyond brief introduction of each FDD method, possibly due to the length of the papers. Therefore, our work is intended to serve as an important complementary review, instead of a replica, of the existing reviews to help readers grasping the research trend and tendency in this fast-developing field.

The reviewed FDD methods in this paper are classified into four categories: time-domain, frequency-domain, time-frequency-domain, and artificial-intelligence-based (AI-based) methods. Since many varieties exist in AI-based methods which involve all the previous three domains, the AI-based methods are treated as a separate category. Popular FDD methods published up to 2010 are briefly introduced, while the focus of the review is laid on the state-of-the-art FDD techniques after 2010, i.e. in 2011–2015 and some in 2016. Therefore, the FDD methods after 2010 are specially summarized and compared in Tables 3, 5, 8, 10 for each of the previously classified FDD categories. The comparisons are in terms of sensor information (type, amount, intrusiveness), applicable condition (stationary/non-stationary, line-fed or inverter-fed) and FDD ambiguity regarding to varying load and unbalanced supply, based on the authors' best understanding of the corresponding references.. Due to the width limit of the tables, lots of abbreviations are used. The abbreviations for FDD methods in each classified type are summarized in Tables 2, 6, 9, 11, respectively, while the abbreviations of other symbols in the comparison tables are shown in Table 4. The major differences between this review and the previous reviews are::

- The core literatures for FDD methods of IMs after 2010 are reviewed;
- Tabulated comparisons of FDD methods published after 2010

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Nomenclature

BF	Bearing fault
BRBF	Broken rotor bar fault
D_b	Diameter of the rolling ball in a bearing
D_c	Diameter of bearing
f_e	Fundamental electrical frequency
f_{rm}	Rotor mechanical frequency
EF	Air-gap eccentricity fault
FCFC	Fault characteristic frequency component
FDD	Fault detection and diagnosis
k_1 to k_{10}	Integers 1, 2, 3…
k_{11}	Integer 1, 3, 5…
N_b	Number of the rolling balls in a bearing
N_d	Order of rotating eccentricity
N_w	Order of stator magneto-motive force harmonics
N_s	Number of rotor slots
P	Number of machine magnetic poles
s	Machine slip
SSWF	Stator short winding fault
δ	Contact angle of bearing

are provided for fast referring;

- A dedicated comprehensive discussion is provided regarding to recent research advances, trends as well as remaining difficulties and possibilities;
- Major types of FDD methods for all the four major IM faults (EF, BF, BRBF and SSWF) are reviewed.

The rest of this paper proceeds as follows: Section 2 introduces the four major types of faults in IMs and their causes; Sections 3 and 4 present different FDD methods in each category and the comprehensive discussion of FDD methods for IMs, respectively; Section 5 concludes the paper.

2. Four major types of faults in squirrel-cage induction motors

The main components in IMs are the stator core and laminations, rotor core and laminations, stator windings, rotor windings or bars, insulating material, shaft, bearings, and housing. As the scope of this paper is limited to IM itself, faults in drives, sensors and other components in a motor drive system are not included.

EF is a mechanical fault when the spacing between stator and rotor varies significantly. There are three types of EFs [5]: static eccentricity, dynamic eccentricity and mixed eccentricity of the previous two, as shown in Fig. 1. SE has constant air-gap spacing at a fixed circumferential position during rotor rotation, but the spacing at different circumferential positions are different. DE has periodically changing spacing at a fixed circumferential position. Misalignment is a common reason for SE, which could move rotor's physical center away from stator center. DE, on the other hand, is more likely caused by oval cores, bent shaft and worn bearings.

Bearings are used to support rotors and to decrease rotational friction, which is shown in Fig. 2. Bearings can fail even with proper use of motor due to fatigue and wear. Insufficient lubrication, high load, enduring operation, high ambient temperature, etc. can accelerate BF. A BF originates from distributed types, such as raceway roughness and waviness, and then develops to local types, such as cracks, pits and spalls [6]. Based on the location of the local fault, BF can be subdivided into four types: inner-race, outer-race, rolling-element, and cage BFs.

Another type of mechanical faults in a squirrel-cage IM is BRBF, which has been greatly studied in the literature. BRBF is mainly caused by intense thermal stress generated from large induced rotor current as well as other electrical, mechanical and environmental stresses. Once one rotor bar is broken, the adjacent rotor bars will have to take over the extra stresses from the broken rotor bar. This fact accelerates subsequent failures in adjacent rotor bars. A broken rotor bar with zero flowing current can be modeled as a healthy rotor with a virtual negatively flowing rotor current that compensates the healthy positively flowing current as if the rotor is healthy. The negatively flowing current generates an additional negatively rotating magnetic field that is usually applied for FDD of BRBF.

The last actively studied fault type is SSWF which is also referred as interturn or turn-to-turn fault. SSWF is defined as an electrical fault and it accounts for majority of electrical failures in IMs [7]. Stator open winding fault is another frequently discussed electrical fault, but not in this paper, since this fault commonly occurs in power converters or drives rather than in IM itself. Interturn insulation breakdown causes SSWF and several factors can contribute to it including thermal, mechanical, electrical and environmental stresses. Readers are referred to [8] for detailed descriptions.

Faults in IMs generate abnormal features in different domains, which are used as fault indicators. These fault-indicative features can be extracted from voltage, current, magnetic, mechanical (vibration), chemical, acoustic, etc., signals using different sensors. The fault indicators in frequency domain are the most popular and well-understood ones since they can be feasibly detected by Fast Fourier Transform (FFT). Among all the feedback signals, stator current(s) of IMs is(are) the mostly used, since current sensors are relatively inexpensive and easy to use, and they are already installed in many motor drive systems for control purpose. Applying FFT on stator current feedback leads to the famous FDD method, Motor Current Signature Analysis (MCSA). Due to the popularity of MCSA, the FCFCs of the four major IM faults in stator current spectrum are summarized in Table 1 for fast referring.

Table 1
FCFCs of the three major IM mechanical faults in stator current frequency spectrum.

Fault	Fault Characteristic Frequency Components		Ref.
EF	DE/ ME (low frequency range)	$f_{ef1} = f_e\left[1 \pm \frac{2k_1(1-s)}{P}\right]$	[9]
	Principal slot harmonics (PSH)	$f_{ef2} = f_e\left[\frac{2(k_2N_s \pm N_d)(1-s)}{P} \pm N_w\right]$	[10]
BF	Inner-race BF	$f_{ir} = f_e + \frac{k_3N_b}{2}f_{rm}\left[1 + \frac{D_b}{D_c}\cos\delta\right]$	[11]
	Outer-race BF	$f_{or} = f_e + \frac{k_4N_b}{2}f_{rm}\left[1 - \frac{D_b}{D_c}\cos\delta\right]$	
	Ball-type rolling-element BF	$f_b = f_e + \frac{k_5D_c}{D_b}f_{rm}\left[1 - \left(\frac{D_b}{D_c}\cos\delta\right)^2\right]$	
	Cage BF	$f_c = f_e + \frac{k_6}{2}f_{rm}\left[1 - \frac{D_b}{D_c}\cos\delta\right]$	
	Inner-race/ Outer-race BF (simplified equation, for bearings of 6 to 12 ball-type rolling element)	$\begin{bmatrix} f_{ir} \\ f_{or} \end{bmatrix} = f_e + \begin{bmatrix} 0.6k_7N_bf_{rm} \\ 0.4k_8N_bf_{rm} \end{bmatrix}$	[12]
BRBF	$f_{brbf} = f_e\left[1 \pm 2k_9s\right]$		[13]
SSWF	$f_{sswf} = f_e\left[\frac{2k_{10}(1-s)}{P} \pm k_{11}\right]$		[13]

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