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Comprehensive Study On Induction Motor Condition Monitoring Techniques And Products – A Review

Ayyappan GS[*¥Ŧ], Poonthalir R[¥,] Raja Raghavan M [¥,] Ramesh Babu B[*†Ŧ], Kota Srinivas [¥Ŧ]
[¥]*CSIR- Central Scientific Instruments Organisation, CSIR Madras Complex, Chennai 600113,*
[†]*Pollution Control Division, CSIR-Central Electro Chemical Research Institute, Karaikudi 630003, TamilNadu, India*
[Ŧ] *Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, 201002, India*

Abstract

Motor systems are critical components and play a vital role in industrial processes. They consume about 50–60% of total plant consumption. Thus, the efficiency of the motors should be maintained. Although they are highly reliable, they are susceptible to many faults due to ageing, improper usage, misuse, and mishandling. Overall, induction motor performance may be affected by the following faults: broken rotor bars, bearings, rotor mass unbalance, bowed rotor, stator winding, rotor winding, single phasing, crawling etc. Any fault can result in high losses with respect to energy consumption, cost and can be dangerous with respect to safety and security. The prior detection of faults and its optimum diagnosis facilitates the industry to operate with the least unexpected maintenance mechanism or industrial shutdown. Various fault diagnosis techniques have been developed over the last two decades. Keeping this in mind, to avoid repetition and to facilitate future research, a brief review is presented. This paper deals about various faults, their possibilities of occurrences, condition monitoring methods, fault signal extraction techniques, and algorithms for early detection and classification.

Keywords: *Condition monitoring, Fault diagnosis, Hybrid Fault Detection, Induction Motor, Motor Current Signature Analysis, Vibration analysis.*

1. Introduction

Although induction machines are relatively reliable and robust due to their simple design and well-developed manufacturing technologies, faults do occur and may severely disrupt industrial processes. Costly machinery repair, extended process downtime, health and safety problems, and high energy consumption have made a trend in modern industry to focus attention on fault detection and predictive maintenance strategies for industrial plant. System maintenance does not only require preventive approaches but also early diagnosis of a developing fault, to allow maintenance personnel to schedule repairs, prior to an actual failure. Energy management of induction motor becomes essential as they are key components in industries. Hence, condition-based maintenance and efficiency estimation of induction motors help in energy management.

2. Classification of Faults

Broadly, Figure 1 shows the types of faults which affect the performance of the induction motor.

Fig. 1: Types of induction motor faults

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These faults in induction motors can cause single or multiple effects like:

- Unstable voltages and line currents,
- Mechanical Vibration and noise,
- Pulsations in torques,
- Excessive heating of the machineries,
- Leakage of electromagnetic flux and so on.

As per the combined survey conducted by Electric Power Research Institute and IEEE-IAS [1], induction machine faults & its contributions are shown in Table I and Fig. 2.

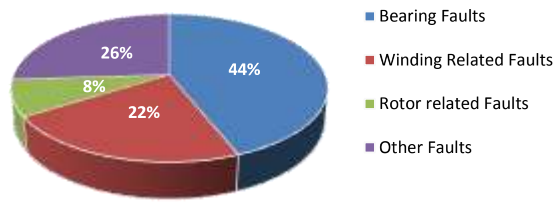


Fig. 2: Induction Machine Faults in Percentile

Table I: Comparison of IEEE, EPRI & Allianz Surveys [2]

Major Components	IEEE-IAS % of Failures	EPRI % of Failures	Allianz % of Failures
Bearing related	44	41	13
Stator related	26	36	66
Rotor related	8	9	13
Others	22	14	8

According to severity levels, faults in an induction motor can be classified as:

a) Non-catastrophic faults with only small effects in operation,
b) Partial catastrophic faults with possible emergency operation and
c) Catastrophic faults with immediate action.

A. Broken Rotor Bar

Mechanical defects contribute to about 40 - 50% of induction motor faults [3]. The rotor is subjected to various stresses that affect the rotor condition and subsequently results in failures [4]. This type of fault is easy to detect using steady state condition monitoring. Fig. 3 shows the view of broken rotor bars. The condition of the rotor is identified [7] based on standards.

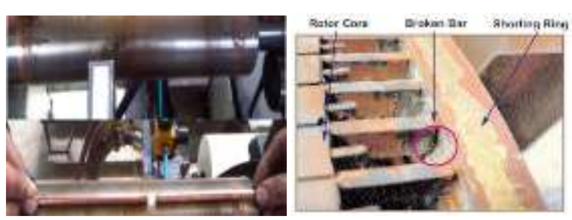


Fig. 3: Photograph of rotor and parts of broken rotor bar [www.hz-electric.com]

The primary causes of broken bars are direct online starting duty cycles and pulsating mechanical loads. Other possible causes for the breaking or cracking of rotor bars include thermal stresses, and/or mechanical stress caused by bearing faults and metal fatigue [5]. This eventually results in an increase in rated current in the rotor bars adjacent to the faulty rotor bar [3]. The resistance due to broken bar would increase and thus more heat is generated. Torque is changed notably by a broken bar and becomes harmful to the steady operation and safety of electric machines [6]

B. Air-gap Eccentricity

If the alignment of the rotor is not centered, then the air-gap will be non-uniform and this phenomena is called the air-gap eccentricity. Air-gap eccentricity prevails in the two forms as static and dynamic eccentricity as shown in Fig. 4.

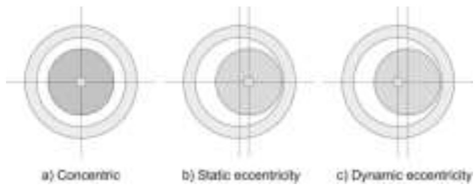


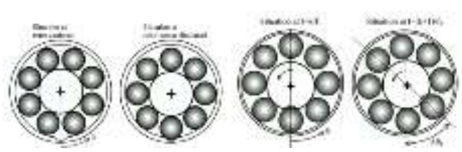
Fig. 4: Types of Air gap eccentricities

In static eccentricity, the length of the radial air-gap is an unchanging factor [8]. In dynamic eccentricity, the minimum radial air-gap length is positioned in such a way that it revolves with the rotor. Mixed eccentricity is a situation in which both the static and dynamic eccentricity coexist. In industrial practice, the allowable fraction of air-gap eccentricity is about 10% [5, 9]. In the worst case scenario, rotor and stator gets defaced when the rotor smears against the stator. Eccentricity faults can potentially introduce other faults and become catastrophic. Air gap eccentricity can also result in noise and/or vibration.

C. Bearing Faults

The construction of bearing consists mainly of the outer and inner raceway, the balls, and the cage. Bearing fault must be addressed as soon as possible. It can be categorized into distributed and localized defects [10]. Distributed defects make them difficult to characterize by distinct frequencies whereas single-point defects are localized and can be classified into:

- Defect in outer raceway
- Defect in inner raceway
- Defect in ball



(a) (b)

Fig. 5: Radial rotor movement due to (a) outer bearing raceway defect (b) inner bearing raceway defect

Fig. 5(a) shows the radial rotor movement due to an outer bearing raceway defect. Fig. 5(b) shows the radial rotor movement due to an inner bearing raceway defect.

D. Stator Winding Failure

Occurrence of stator failure gets swayed by either electrical, mechanical, thermal or environmental tensity or a combination of them [4]. The stator faults can occur in the (i) laminations and frame of stator and (ii) stator winding [11], [13]. Inter-turn, winding short circuit, phase-to-phase short circuit [12], etc are some of the more pervasive and potentially harmful faults in the stator. Fig. 6 shows view of the stator with different faults. Stator winding problems are identified by observing the stator slot passing frequencies.

Fig. 6: Some of the faults that occur in stator winding

A fuse that is operated in open circuit, flop of circuit breaker, or any connections, may be some of the impetus to short circuit failure.

E. Unbalanced Supply Voltage

If the three phase voltages in an induction motor differ in amplitude or do not possess 120° phase relationship or both coexist, then voltage unbalance is said to have occurred. The consequences of unbalanced voltage are the start-up transients, dynamic performance and variation in the steady state characteristics of the three phase induction motor.

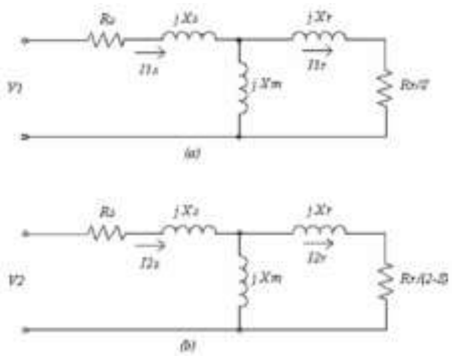


Fig. 7: Equivalent circuits of (a) positive and (b) negative sequences

The Voltage Unbalance Factor (VUF) as expressed by International Electro-technical Commission (IEC) is [14]

$$\% \text{ VUF} = \frac{\text{Vn}}{\text{Vp}} \text{ X } 100 \%$$

Where Vn and Vp are magnitudes of negative and positive sequence voltage components respectively.
As little as 1% voltage unbalance can cause motor protection circuit to trip. A blown fuse at any one phase of a three-phase capacitor bank [15] may also be a cause for voltage imbalance. Voltage unbalance greater than 5% can be caused by single-phasing conditions, during which one phase of a three-phase circuit is missing or de-energized.

F. Load Torque

At steady state, most electromechanical systems are operating with constant load torque which the induction machine has to equalize at all times. In some cases, running the induction motor at variable load, strains the shaft [16]. After applying the variable load torque on the shaft, rotor of induction motor starts to oscillate around a constant mechanical angular velocity which is proportional to the average load.

3. Condition Based Monitoring

In general, there are three types of maintenance techniques — pre-emptive maintenance, responsive maintenance and anticipative maintenance. In preventive or periodic maintenance, the maintenance on the machine is carried out at a regular periodic manner at a fixed frequency. Reactive or breakdown maintenance refers to reacting to the need for maintenance of the machine, because the machine has failed completely. In anticipative or condition based maintenance, the maintenance is done on the machine depending on its need [17]. Though, it is initially expensive because of the additional requirement of an instrumentation system, it is more economical in the long run.

Fig. 8: Prominence of Condition Monitoring

The conclusive end in the process of diagnosing the induction motors by the presence and absence of condition monitoring [1] is given in the Fig. 8. Condition monitoring in an induction motor intents to [17]:

- Reduce production loss caused by failures,
- Increase process efficiency,
- Extend the operating life of plant systems,
- Reduce overall maintenance costs,
- Increase overall profit,
- Anticipate the equipment failure and
- Ameliorate the accuracy in incipient failure prediction.

Table II shown emphasizes the need of condition monitoring and fault diagnosis of electrical motors [18].

Table II: Expected reliability improvement with comprehensive monitoring

Speed Range (721-1800 rpm)	%Reliability Without Monitoring Aid (1st year)	%Reliability With Monitoring Aid (1year)
201-500 HP	92.6	96.8
501-5000 HP	91.1	96.5
>5000 HP	90.7	95.5

The main steps adopted in condition based monitoring are [19]:

- Signal Monitoring
- Signal Processing
- Signal Interpretation

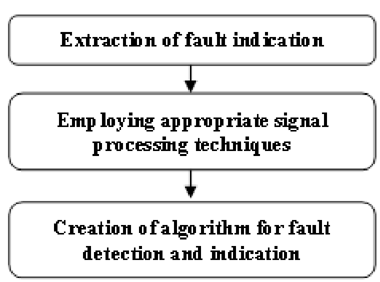


Fig. 9: Condition Monitoring Scheme

4. Signal Monitoring Methods

With increasing dependence on electrical apparatus, condition monitoring is becoming more and more important. In recent years, various fault detection techniques have been developed in diagnosing the fault-related signals.

G. Flux Monitoring

Dorell et al had discussed the condition monitoring of induction motors through the analysis of stator current, air gap flux and vibration signals [20]. Galina Mirzaeva et al had proposed a comprehensive fault diagnostic system which measures the air gap flux density using hall-effect flux sensors [21], [27]. Irahis Rodriguez et al had shown the detection of stator winding failures, broken rotor bars and end ring faults using the motor flux signature analysis [22].

H. Thermal Monitoring

Rotor and stator temperature rise in induction motors is considered to be a major cause of motor insulation degradation and motor failures [23]. Measurement of local temperature aids in thermal monitoring of electrical machines [1]. The analysis of the finite element results shows practically the same time variation and amplitude of the stator currents for the healthy motor and for the two faulty cases – one broken bar and rotor dynamic eccentricity [25]. Though the FEA model is highly time-consuming and computation-intensive, it has an advantage that it is more accurate [24]. Rotor hot spot monitoring is very difficult. One challenge is bringing the temperature signal off the rotor. Point temperature sensors for rotor windings have been developed for research purposes [26].

I. Torque Monitoring

The pragmatic hitch is that it is not possible to measure the air-gap torque straight away [28]. The torsion spring system comprises of a rotor, shaft and mechanical load [29]. The air gap torque attenuates differently for different order of harmonics of the torque components [1].

J. Electrical Monitoring

Electrical monitoring is implemented using Current Signature, Park's Vector, Zero sequence and Negative sequence current monitoring [30]. Motor Current Signature Analysis (MCSA) involves the use of motor current and voltage signals. The stator current is then subjected to spectral analysis [31]. The detection of various faults is based on the behavior of side bands associated with the faults [24]. Benbouzid et al investigated the efficacy of current spectral analysis on induction motor fault detection [32]. The frequency signatures were identified for asymmetrical motor faults, including air gap eccentricity, broken bars, shaft speed oscillation, rotor asymmetry, and bearing failure [33]. The various advantages of MCSA are discussed in [35]. The accuracy of the spectrum depends on the measured current. Commercially available current clamps may be used with a well-defined range, accuracy and bandwidth. The motor current is measured with some commercially available current clamps with the following properties [36]:

Sensitivity	: 1 mV/A
Bandwidth	: 10-20 kHz
Range	: 2000 A
Accuracy	: ±0.2% rdg ± 1% range

K. Power and Speed Measurements

Motor power signature analysis is focused on the detection of double-slip frequencies present in the electric input power spectrum similar to MCSA [37]. Detection of the occurrence of rotor mixed faults in induction motors is implemented by performing spectral analysis of the instantaneous power [38].

L. Noise and Vibration Monitoring

Noise and vibration are present in electric motors and analysis of them can provide potential information about the condition of the motor [30]. Noise monitoring is done by measuring and analyzing the acoustic noise spectrum [1]. Ellison et al had shown the detection of air gap eccentricity using this method [39]. Vibration based diagnosis can detect bearing faults, rotor eccentricities, gear faults and unbalanced. Li et al had carried out the diagnosis of bearing fault using vibration monitoring [40]. Jack et al had used an approach which uses genetic algorithm and artificial neural network, achieving an accuracy of 99.8% [41]. The major limitation of vibration monitoring is its cost of implementation. The accuracy of vibration measurement depends on the mounting of the sensors and expertise is needed [20], [42], [43]. Abdelmalek Khezzar et al had proposed an approach based on spectral analysis of line-neutral voltage i.e. voltage taking place between the supply and the stator neutrals for broken rotor bar detection[44]. Rangel Magdaleno et al had presented a novel methodology for half-broken-bar detection, which combines current and vibration analysis [45]. Yang et al, in different studies, had proposed an advanced scheme that uses stator current and vibration signals for fault diagnosis [46], [47], [48].

5. Signal Processing Techniques

The signal processing techniques play a major role in assessing the condition of induction motor. It involves processing the observed signal from the sensors to get useful information. It is a highly efficient approach for performing time – frequency domain conversion by factorization of Discrete Fourier Transform (DFT) matrix into a product of sparse factors. In practical application, the execution time can be reduced with higher degree and in such scenario; the enhancement is approximately in relation with N / log (N). Thus, Fast Fourier Transform (FFT) technique becomes more useful in a wide variety of applications, from digital signal processing to algorithms for quick multiplication of large integers.

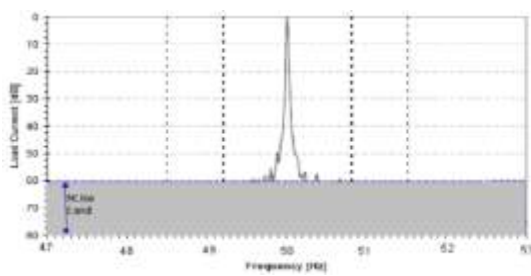


Fig. 10: Current spectrum of a healthy motor using FFT

For on-line spectral analysis, the wavelet based detection method shows good sensitivity, and helps in incipient fault detection. Levent et al had employed wavelet packet decomposition to the stator current for uncovering the faults in the bearing [49]. Szabo Lorand et al had applied the wavelet transform to detect the faults in the rotor [50], [51]. Jose A Antonino-Daviu et al and Hew Wooi Ping et al had proposed discrete wavelet transform (DWT) for the detection of rotor bar failures [52], [53].

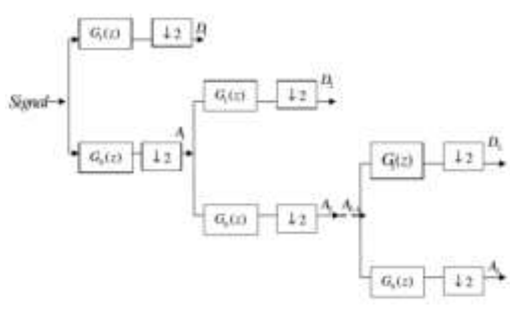
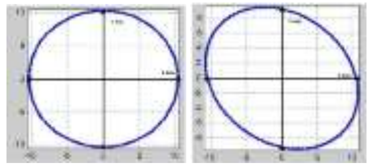


Fig. 11: Discrete Wavelet Transform

Szabo Lorand et al had shown the use of Park's vector for detecting the faults in rotor [54]. Izzety Onel et al had investigated the detection of bearing damages through MCSA using Park's transform [55]. Izzety Onel et al had diagnosed the bearing faults by the application of park vector [56].



(a) (b)

Fig. 12: Park's currents vector of(a) healthy motor (b) faulty motor

Benbouzid concluded that the analysis of stationary signals can be done using Fourier analysis [32]. However, it is not appropriate for analyzing the signal that has a transitory characteristic. To overcome this problem, Fourier analysis had been adapted to analyze small sections of the signal in time. This technique is known as short time fast Fourier transform (STFT).

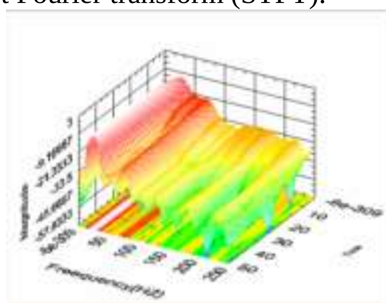


Fig. 13: STFT of a healthy motor

Mohamed El Hachemi Benbouzid et al [57] had briefly presented various signal processing techniques available condition monitoring of induction motors. The pros and cons of the signal processing techniques are briefly discussed.

Table III: Comparison of various signal processing techniques

Technique	Required measurement	Faults diagnosed	Pros	Cons
FFT	One phase current	➢ Bars in rotor being broken ➢ Short-turn in winding fault ➢ Air-gap eccentricity ➢ Bearing faults ➢ Load fault	Easy to implement	➢Lost time information ➢Not effective at light load condition
Wavelet transform	One phase current	➢ Bars in rotor being broken ➢ Short-turn in winding fault ➢ Vibration faults	Suitable for varying load and light load conditions	Require expertise
Park vector	Three phase	➢ Short-turn in	Easy to diagnose the	Not effective for load

approach	current	winding fault ➢ Bearing faults	fault	faults and broken rotor bar fault
STFT	One phase current	Bars in rotor being broken	➢Fast speed ➢Suitable for varying load condition	➢Poor frequency resolution ➢Analyse signal with fixed sized window

6. Data Interpretation Algorithms

In recent years, the techniques for condition monitoring of induction motors have undergone transformation from traditional methods to Artificial Intelligence (AI) techniques [58]. Nowadays, AI-based techniques which use fuzzy logic, neural network, particle swarm optimization [59] and so on are so popular among researchers. AI techniques are good candidates for the labor-saving procedures in induction motor fault diagnosis [60]. The motor fault diagnosis was implemented by an adept system [61]. A system for effective fault detection in a three phase induction motor was developed based on neural networks and fuzzy logic [62].Fuzzy logic was first developed in the mid-1960s for representing uncertain and imprecise knowledge [63].The fuzzy logic tool provides a technique to deal with imprecision and recently attracted researchers attention for different applications like fault diagnosis.

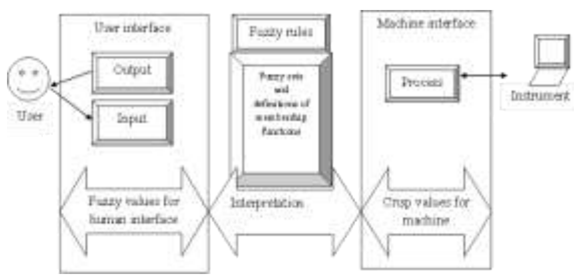


Fig. 14: A Typical Fuzzy Logic Controller

Many studies had been carried out in the field of condition monitoring of electric motors using fuzzy inference systems [64-67]. Hybrid techniques involving neural networks and fuzzy logic are emerging for use in condition monitoring of rolling bearings [69], [129]. Artificial neural networks (ANN) mimic the neural connections in the human brain. Asiri et al had made use of neural networks and diagnosed six types of partial discharge and analyzed them based on the location of partial discharge activity [70].

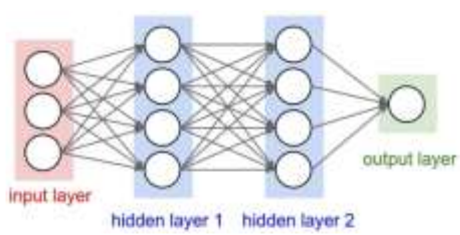


Fig. 15: Structure of a neural network

In the technique of ANN, each artificial neuron (shown as a circle) acquires a set of inputs, puts in pre-set weights to each of the inputs and outputs a non-linear result [71].

Table IV: Comparison of various signal interpretation algorithms

Features	Parameter estimation	AI			Statistical analysis
		Expert system	ANN	ANN-Fuzzy	
Machine model	Yes	No	No		No
Fault mechanism	Yes	Yes	No		No
Heuristic knowledge	Useless	Useful	Useful		Useful
Dependence on samples	No	No	Yes		Yes
Complexity	Difficult	Difficult	Simple		Simple
Performance	Fair	Good	Fair		Good
Variables measured	I_s, V_s	I_s, V_s	I_s, ω		I_s

7. Condition Monitoring Products

AREVA purveys an EMPATH™ system which measures and analyses the stator current and voltage of the motor, and helps in acquiring the potential information of critical processes and machines. It requires a laptop or computer with special signal conditioner, digitizer and a proprietary software and has provisions for both storing of data and puts on view the time-domain and frequency-domain signals. The signal conditioner acquires both three phase voltage and current signals, and outputs MCSA-filtered signals.

ALL-TEST Pro has introduced a complete solution for electric motor system health and motor diagnostics. The ALL-TEST PRO 5™ provides its support to all types of motors, ranging from induction, synchronous, AC, DC, brushless DC, servo and wound rotors to single phase motors. It has a touch-enabled user interface and the capability to store more than 650 test data.

ABB's condition monitoring solutions provide reliable information on the condition of motors and generators. ABB MACHsense-P uses vibration and electrical data from motors in order to diagnose problems. It addresses problems in four crucial areas: rotor winding, bearings, overall mechanical condition and power supply quality. ABB MACHsense-R processes the raw vibration and temperature signals to cover potential fault areas: cage rotor, bearings and overall mechanical condition. ABB LEAP produces an actual lifetime estimate for the stator winding insulation.
Motornostix is an integrated system for on-line condition monitoring of electric motors, gearboxes, pumps, compressors and various other machineries. It is an intelligent web enabled advanced monitoring system.

AnomAlert Motor Anomaly Detector is a system to identify extant and evolving faults in machines continuously. The anomaly detection is achieved by measuring the current and voltage signals supplied to the motor and decision is made based on a knowledgeable and model-based approach . The system requires permanent installation and is applicable to three phase AC, induction or synchronous, fixed or variable speed motors.
Artesis MCM uses a mathematical modeling technique to detect and diagnose faults in electric motors and connected equipment. It automatically assesses the severity of any variations from normal operation and presents the results of its sophisticated analysis to the user in a simple, compelling traffic light display.

Induction Motor Performance Analyzer (IMPA), developed by CSIR-CSIO Chennai Centre, is a product for monitoring the performance of induction motor on-line, on-site and in-situ. IMPA employs proprietary algorithm to estimate the equivalent circuit parameters of a motor at any load condition, without detaching the motor from field and without conducting No-load and Blocked Rotor Tests. IMPA estimates the operating efficiency of the motor without measuring the output power and torque. The product and the algorithm are verified for their performance as per IEC60034-2-1 standard at Motor Test Centre established at its campus.

8. Comments and Inferences

An accurate and efficient means of condition monitoring and fault diagnosis can drastically improve reliability and stability of the machine. This paper has reviewed the available techniques in the present scenario for signal capturing, conditioning, signal processing, analyzing and reporting the health status of the motor directly or indirectly.

Vibration based fault analysis is a very old and well-established technique for the detection of mechanical faults in an induction motor at site. Each fault in a motor has a unique vibration signal, which varies in terms of its amplitude, frequency and phase displacement. Yet, it needs expensive accelerometers and associated wiring. It requires access to the machine. For accurate measurements, sensors should be mounted tightly on the electric machines, and expertise is required in mounting and handling. This technique also requires skilled and trained manpower for carrying out spectral analysis and to diagnose the faults in an induction motor. Vibration in any machine becomes predominant when the fault is more aggressive. Hence, early detection of faults may not be possible. Many products, which use vibration-based analysis for fault detection, exist in the global market.

MCSA has been utilized for the identification of both electrical and mechanical faults. This is the most feasible, cheapest and non-invasive technique for any electrical fault detection. This method has been accepted by many researchers for studying and characterizing signals and faults, under different load conditions and abnormal operating conditions. This method enables the faults to be detected at their early stage of occurrence. However, fault detection using MCSA may lead to false-positive and false-negative conclusion. There are few products available in the global market which uses MCSA and are more expensive.

Detection of multiple faults may be complicated because of the inter-relationships of the fault signals. This can be rectified by employing multiple sensors and signal processing techniques. The existing research makes use of a single sensor type, blended with a signal processing technique to detect a fault. The certainty of the fault detection can be improved by conjoining the information from multiple sensors and signal processing techniques. ABB has come up with a solution, which combines MCSA and vibration analysis as a hybrid technique. It captures the vibration and MCSA data on-site and displays only the status as healthy or unhealthy locally. The captured data is then transferred to the far end through Cloud server and computing is done on the data and report is supplied to the concerned industry on chargeable basis.

Hence it is concluded that there is a need to work on hybrid measurement and hybrid optimization techniques. This may include vibration, MCSA and thermal analysis, for capturing, processing and analyzing the signals. Hybrid decision-making/optimization algorithms like Fuzzy or ANN may be a pre-requisite for reliable fault diagnosis. Eventually, this may cover the entire spectrum of faults, early warning and reliable detection. This paper has provided a brief review on current research in condition monitoring and has identified key areas for future research.

9. Conclusion

This paper is aimed at providing a brief information on the various faults, their major causes, their effects on different machine quantities like current, torque, vibration, noise, flux etc. The corresponding current signatures of the faults are also introduced. The diagnostic methods of the faults from the symptoms are summarized. This paper highlights and summarizes the future scope for research work and the need for development in the domain of health assessment of induction motors.

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