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A Comprehensive Review of Condition Based Prognostic Maintenance (CBPM) for Induction Motor

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ABSTRACT This paper presents condition monitoring aspects of induction motor, its present status with possible mitigation schemes and future maintenance challenges. The induction motors constitute the major portion of motors in domestic and industrial applications. These motors experience different types of failures and faults associated with insulation, bearing, stator, rotor, and eccentricity. As a matter of fact, these faults may subsequently enhance the probability of failures unless proper introspection is not accomplished. In order to reduce the failure time and operating cost, early detection is indispensable which necessitates condition-based approach on contrary to scheduled maintenance. The condition monitoring is a strong candidate to address the diagnosis of machinery failure problems and unreliability. In this context, a comprehensive analysis is reported in the literature with a focus on different methodologies being addressed for such objective. Utmost efforts are made to comprehensively analyze in the reported literature in a sequential manner citing the advantage and limitations in this paper. The authors hopefully described and illustrated the associated problems with possible mitigation in the context of condition monitoring which would be immensely helpful for future researchers working in these aspects and the future roadmap would be clearly reflected.

INDEX TERMS Condition monitoring, induction motor, bearingless induction motor, fault diagnosis, artificial intelligence, wavelet techniques, deep learning.

I. INTRODUCTION

Induction machines are the most frequently used electrical machines in domestic and industrial processes. Around 85% of motors used in industrial appliances are induction machines. The main reason behind it is lower cost, ruggedness, robust in structure, lower maintenance requirement, easiness in availability and capability to work under severe working atmosphere [1]. The fault in the induction motor distracts the overall production of the industry, which may lead to increase the idle time and losses of revenue. In order to decrease the down time and for reliable and safe operation, fault recognition in early stage is desirable which necessitates condition-based monitoring of the induction motor.

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The basic principle of condition monitoring (CM) lies on investigating the running characteristics of the machine such that prediction for maintenance is done prior to breakdown or deterioration to occur in order to introspect the health monitoring of the machine. In this context, the individual part's life or the life of the whole machine is critically analyzed. In this direction the correct data acquiring process and the data analysis is done in order to capture the trends that might occur [2]–[4]. The maintenance based on time investigate the machines repair in offline mode in accordance with time schedule are working hour that leads to avoid the probability of failure. However unwanted shutdown or sudden accidents that may occur in the stipulated period should be taken into account in order to explore the health of the equipments [5]. Thus fast fault detection in early stage can improve the performance of the motor and reduce the consequential harms, breakdown repairs, decrease the cost of maintenance and

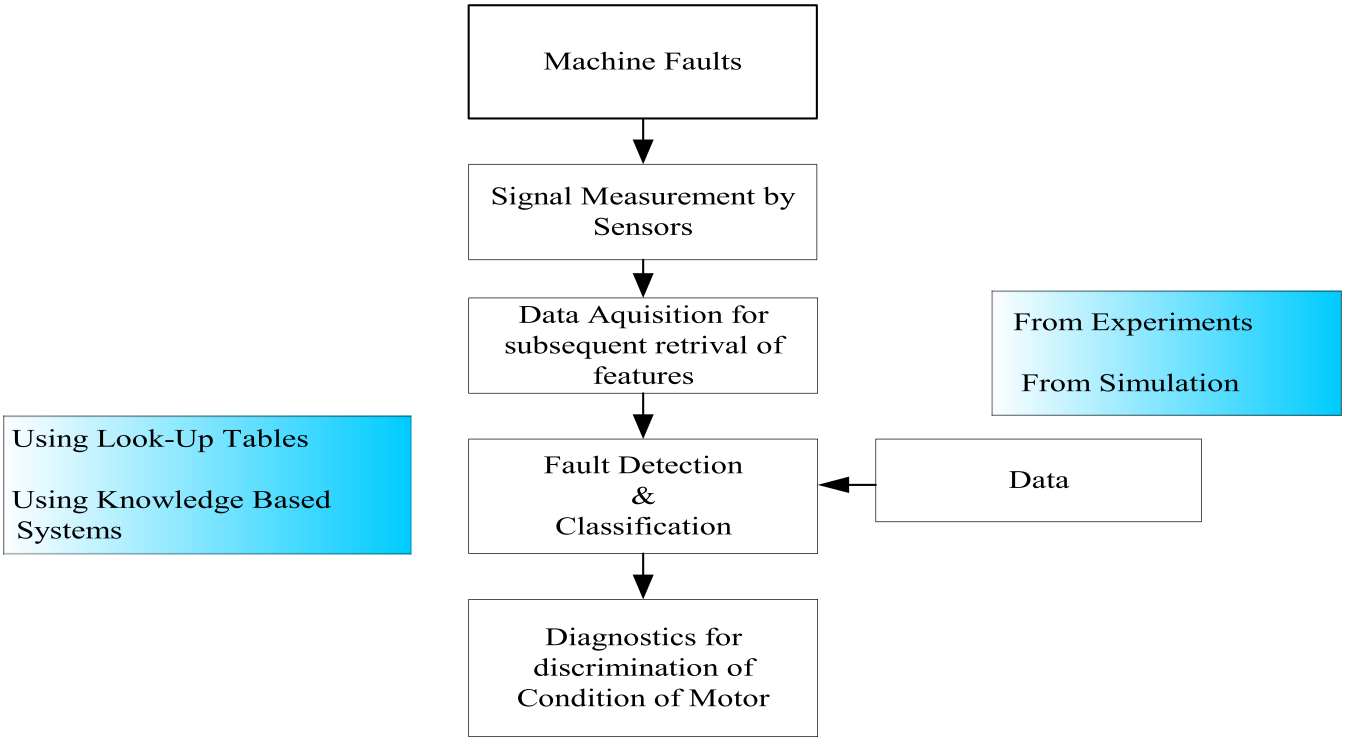

FIGURE 1. General Over-view of fault-diagnosis systems.

unpredicted failure risk is remarkably reduced with the availability of the machine. Accurate identification scheme urges the methodologies to be implemented in the direction of condition-based preventive and predictive maintenance rather than conventional time-based maintenance. In this context, the focus of condition based repair is to illustrate the evaluation accurately and identifies the fault a prior. Condition based maintenance leads to the set of information about the machine's state and focuses CM approach followed by efficacy of the type of maintenance needed in order to reduce the manpower. The said scheme would not lead to halt the machine accidentally [6], [7].

The schematic overview of the block diagram representation of the fault diagnostic scheme is mentioned in Fig. 1. The procedure step of the condition monitoring is carried out in a sequential manner as described in subsequent subsections.

(i) Signal measurement by sensors: Sensors or actuators are integral components for transformation in order to convert the physical quantity into an electrical signal. The physical quantities will be monitored if there is any detectable physical change in it which can interpret the failure due to incipient fault much prior to failure leading to catastrophic scenario. The sensor selection will solely depend upon the monitoring methods as well as failure mechanism of the machine.

(ii) Data acquisition for subsequent retrieval of features: Data acquisition is an important unit for pre-processing of the signals followed by required amplification after the data is retrieved from the sensors. The communication technology for data transfer is vital for data acquisition system which would be realized by microcomputer.

(iii) Fault detection and classification: The prime objective of the fault detection is to analyze the incipient fault associated with any part of the machine so that further analysis can be initiated. Feature extraction and Model-reference based method are two important methods to accomplish the fault diagnostic objective. For frequent methodology for extraction of feature, the signal processing technique based on both time and frequency would be essential to analyze the signature in order to discriminate the faulty condition with that of the healthy condition of the machine.

(iv) Diagnostics for discrimination of healthy and faulty condition: The abnormal detected signals need to be post processed for making a clear sign of repairs. Diagnostics is carried by the experts both in off line as well as online which can make a clear cut map for the implementation of advanced technologies in this regards.

Followed by Section I; Section II of this paper describe various faults that do exist in induction motor with the probability of its causes and subsequent effects on frequency spectrum. Further Section III illustrates the different techniques of condition monitoring which would focus on the fault monitoring associated with induction motor. Section IV represents advanced fault diagnostic techniques being implemented for induction motor. Subsequently, Section V represents the motor fault diagnostic techniques using Artificial Intelligence and Deep Learning. Finally, Section VI concludes the concatenation of the various sections and further discusses the roadmap of research pertaining to induction motor analysis with thrust of condition monitoring.

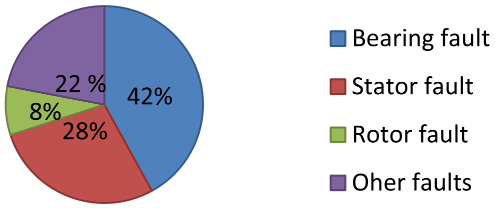

FIGURE 2. IEEE study results on induction motor faults.

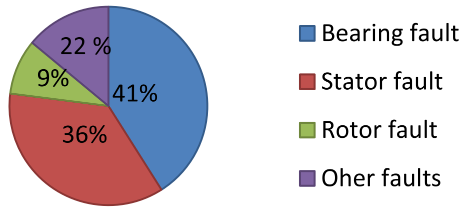

FIGURE 3. EPRI study results on induction motor faults.

II. INDUCTION MOTOR FAULTS AND THEIR ROOT CAUSES

In order to introspect the weakest component in electrical machines, which are susceptible to failure, some statistical analysis about the failures of the machine are discussed in this section. Different cases of motor failure have been analyzed in two different agencies i.e. IEEE and EPRI which are: (i) An analogous analysis on the vital failure of components of motors in powerhouse has been studied by IEEE-IGA. This study is reported by the motor manufacturers. (ii) Beneath the sponsorship of EPRI about industry assessment, study has been carried out by General Electric Company. for evaluating the power house motor's reliability and also to examine the different operating characteristics [8]. This study gives the cause for actual motor faults. The induction machine faults comparative studies as per EPRI and IEEE standard are mentioned in Fig.2 and Fig.3 respectively.

Generally induction machine is susceptible to numerous failures. The prime sources of induction motor faults due to internal, external as well as environmental are depicted in Fig. 4. Internal failures can be distinguished with respect to their sources, i.e. mechanical and electrical or to their place, i.e. rotor and stator. Fig. 5 represents the induction motor fault tree and there causes, where the faults are categorized according to their location.

These faults have been categorized according to the main parts of a machine – faults associated with the stator, faults associated with a rotor, bearing related faults and other faults.

A. BEARING FAULTS

About 42% of induction motor faults are due to failure of bearing according to studies of the IEEE and EPRI as depicted in Fig. 2 and Fig. 3. The induction motor bearing comprises of an outer ring, inner ring and with a set of rolling elements called balls placed in raceways spinning inside the rings. The fatigue failures may causes because of the continual stress on these bearing. Whenever there is failure in bearing it results in certain vibration which influences the eccentricity in air gap between the rotor and stator, also increases the noise levels. Improper insulation, corrosion, contamination, improper lubrication is the factors that are also responsible for the bearing failures. Failures that occur in bearing are cyclic as well as non-cyclic. Based on the position of failure, the cyclic failures may further be categorize as inner race defect, outer race defect, cage fault and defects in ball. Acyclic failure produces an impact amidst raceway and bearing results in a determinable vibration [9]. The vibration frequencies produced by these failures can be expressed as

$$f_o = \frac{N_b}{2} f_r \left(1 - \frac{d}{D}\cos \emptyset\right) \quad (1)$$

$$f_i = \frac{N_b}{2} f_r \left(1 + \frac{d}{D}\cos \emptyset\right) \quad (2)$$

$$f_c = \frac{1}{2} f_r \left(1 - \frac{d}{D}\cos \emptyset\right) \quad (3)$$

$$f_b = \frac{d}{2D} f_r \left[1 - \left(\frac{d}{D}\cos \emptyset\right)^2\right] \quad (4)$$

where

f_o is the frequency of outer race,
f_i is the frequency of inner race,
f_b is the frequency of ball defect,
f_c is frequency of cage failure.
N_b is the number of balls in bearing,
f_r is rotor speed,
d is diameter of ball and D is pitch diameter. Since the bearing vibration leads to ripple in output torque of the motor and therefore the current harmonic spectrum at definite frequency, the spectrum of the current may also be used to inspect failures in bearing [10]:

$$f_{cur} = \left|f_i \pm nf_c\right| \quad (5)$$

where f_{cur} is current harmonic, f_i is source frequency to the motor; f_c is characteristic vibration frequency as given in eq. 5; and n is an integer. Also, it is mentioned in [11] the bearing faults also produce rotor eccentricity, thus produces other harmonic components in the spectrum of current signature. Various causes of the bearing failure are (i) Overload, tight fits and immense temperature rise, thus strengthening ball materials as well as races.

They may further destroy the bearing lubrication. (ii) Fatigue failure: Fatigue failure occurs due to the prolonged run of the bearings causing the fracture of balls. These types of bearing failures are catastrophic in nature. It can increase vibration as well as the level of noise in motor [12]. (iii) Bearings, when exposed to corrosive atmosphere, may deteriorate the lubricants of the bearing [12]. (iv) Contamination: it is the most important factor of bearing failure of the motor. The lubricants get polluted by dirt, other particles which generally exist in environment of the industries. Contamination may result in high vibration and wear. (v) Lubrication failure: it is due to the bearing temperature excessively high; the lubricant runs out from the bearing. (vi) Misalignment of bearings: due

FIGURE 4. **Prime sources of induction motor faults.**

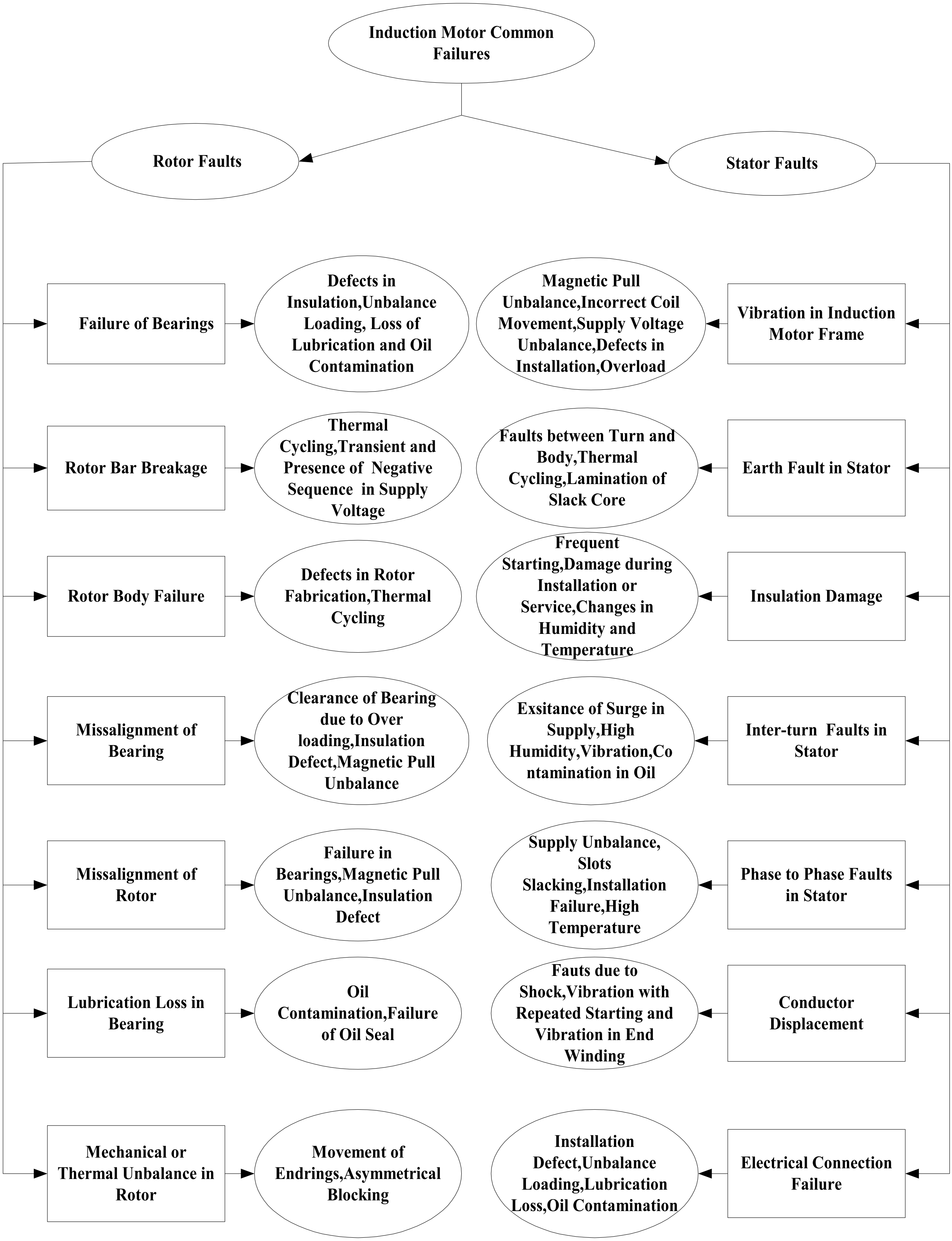

FIGURE 5. Conventional induction motor faults and their causes.

to misalignment of bearings, wear and tear on the surfaces of races and balls takes place, leads to further temperature rise of the motor bearings. It is viewed that any faults in the bearing as discussed above leads to increase in bearing temperature and further raises the vibration in motors. Bearing vibration and temperature information states the bearing condition and therefore machine health [12], [10].

Some authors have proposed bearing less motor in order to solve the problems related to bearing faults. Authors [13] have suggested in enhancing the control precision and dynamic performance of a permanent magnet biased active magnet bearing system in a magnetically suspended directly driven spindle system. The 4-DOF PMBAMB as proposed have inherent character of parameter variation and is more prone to external disturbances. Novel control architecture based on neural network inverse and 2 –DOF internal model control has been put forward. The proposed methodology when cascaded with the inverse of the 4-DOF original system gives better tracking; disturbance rejection also mitigates the effects of unmodelled dynamics improving accuracy outdoing the traditional decentralized PID control scheme. The authors [14] have put forward an innovative methodology for bearing-less permanent-magnet synchronous motor on contrary to permanent magnet motors prone to bearing failures. Authors have suggested a unique control scheme incorporating neural network inverse and 2-degree of freedom internal control architecture. Conventional control schemes comprising of PID controllers are more prone to get affected by load disturbances, changes in speed as well as by parameter variations. The proposed control framework poses better precision in set point tracking as well as disturbance rejection criteria as compared to traditional internal controls. Decoupling control of BPSM is proposed by NNI and 2–DOF internal controllers. BPSM being mathematically complex to model has been addressed by model inversion followed by cascading the original model creating a decoupled control framework. Tangent activation function used to train the feed forward neural network by back propagation learning algorithm, prove to make the system more precise and disturbance free. Authors [15] have proposed a novel rotor architecture framework including V shaped permanent magnets so as to enhance the torque density as well as suspension performance of bearingless permanent magnet synchronous motor. The paper also focuses on the current research on flywheel battery storage for electric vehicles. Static electrical as well as magnetic characteristics like inductance and electromagnetic torque have been studied as well showing low cogging torque as well as large reluctance torque. Finite element method is used for the analysis of the proposed IBPMSM (Interior bearingless permanent magnet synchronous motor).Experimental results prove to be noteworthy in stabilising suspension operation with control architecture framework of optimized BPMSM. Authors [16] have put forward the concept of flywheel energy storage containing a bearingless five phase flux switching permanent magnet machine consisting of E-core stator. Topology as well as the structure of the machine is established. Based on the trial and error method as well as simple variable the stator/rotor parameters are optimized. Simulation results based on the proposed methodology shows an increase in torque by about 16.7% and suspension forces by 15(130 to 145).The variations of not only torque but also suspension have shown a clear indication of diminishing behavior as well.

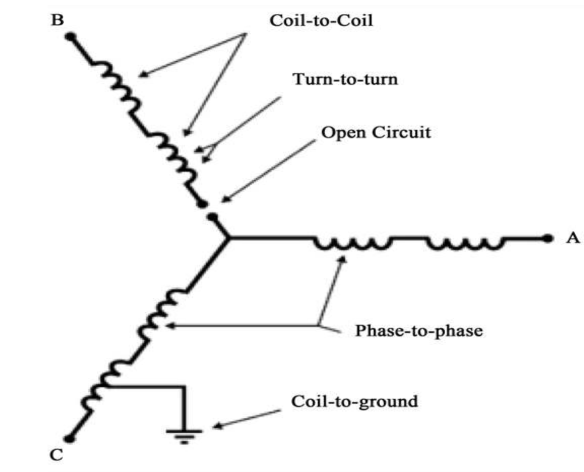

FIGURE 6. Different types of failures in stator winding.

B. STATOR FAULTS

The most frequent failures in induction motor are the stator failure. The winding faults associated with stator winding are often caused by failure of insulation of winding, which leads to local heating. If unnoticed, this local heating further damage the insulation of stator winding till catastrophic failure may occur [17].

Stator failure may be categorized as (i) failure in stator winding (ii) faults in stator frame and (iii) failure in laminations of the stator core. Among these, stator winding failure is the most severe failure. As per IEEE and EPRI studies as shown in Fig. 2 and Fig. 3, faults in stator winding are about 28-36% of total faults that may occur in the induction machine. This failure is because of the failure of stator winding insulation. This fault is also known as short circuit inter-turn fault. Faults in stator winding are categorized as (i) short circuit in turns of the same phase (ii)short circuit between two phases (phase to phase fault) (iii) short circuit into coils of same phase (coil to coil fault) (iv) short circuit that occurs in the phases of entire turns (v) open winding failure when winding get split. Stator winding failures of different categories are revealed in Fig.6 [12].

Various origins of the faults in the winding of stator are (i) Mechanical stresses, which are caused by stator coil movement and striking of rotor on the surface of stator [18]. Movement of coil produced the current in the stator coil (since the force is proportionate to square of current in stator coil) [19] might destruct the insulation of the copper conductor and rotor might too strike the stator of the motor due to misalignment of rotor-to-stator / deflection in shaft / failure in bearing then this striking force leads to puncture of insulation of coil

TABLE 1. Life of winding with rise in temperature.

Ambient Temperature (°C)	Life of Insulation (Hours)
30	250,000
40	125,000
50	60,000
60	30,000

follow on coil to ground failure. Higher mechanical vibration in stator winding results to open-circuit failure [20].

(ii) Electrical stresses, which are due to transients in supply because of various faults that exist which is line-to-ground/line-to-line/three phase fault, circuit breaker opening/closing operation, lightning and drives with variable frequency [18]. These transient voltages degrade the life of stator winding; can also cause turn-to-ground/turn-to-turn failure. (iii) Thermal stresses, which are caused by thermal overloading are the key root for insulation degradation of winding of the stator. It happens due to the excess current, which is in turn caused by continuous overload/unbalance in supply voltage/ obstructed ventilation/ higher ambient temperature etc. [18]. In presence of unbalance per phase in supply voltage of 3.5%, the winding which is carrying the highest current may see a temperature rise of 25% [22].The winding temperature may also increase due to frequent start and stop of the machine. It has been shown in [21] and [22] that the life of insulation of the machine winding may reduce by half for every 10 °C increase above the temperature limit. The change in life of insulation of the winding with rise in temperature above ambient [22] is depicted in table 1.

(iv) Environmental stresses are due to the operation of a motor in conditions which is too cold/humid/hot. Also, the stator winding insulation may get contaminated in such operating conditions causing degraded heat dissipation which may finally reduce the insulation life of the machine [23].

C. ROTOR FAULTS

Rotor cage failure (broken rotor bar/end-ring) occurs around 5–10% of total faults occur in induction machine [24]. There are numerous reasons for which faults in the rotor may arise in an induction machine [25]. For medium voltage motors, faults in cage of the rotor are more prevalent than in case of motors of small size because of immense thermal stress on rotor of the machine. Usually rotor broken bar may be originating by the following reasons: (i) Thermal stresses which are produced by thermal overloading and overheating of the rotor thus leading to thermal expansion of the cage. (ii) Magnetic stresses due to electromagnetic forces as well as pull due to magnetic unbalance. (iii) Dynamic stresses owing to torques at shaft.(iv)Environmental stresses because of contamination in rotor material. (v) Mechanical stresses caused by loose laminations etc. In medium voltage motors, broken bar in rotor or failures of end rings are prime cause of excessive thermal stresses in initial period [26]. Now if one of the bar break, sidebars will bear larger currents that may lead to huge thermal and mechanical stresses which are imposed on these side bars. Now if rotor still rotates, the side bars get damaged [27] and it may extend, leading to rupture of multiple rotor bars. These broken bars fault may create a train of sideband frequencies [28], [29] in the stator current signature which is shown by eq. 6 below:

$$f_{br} = f_{in}\,(1 + 2ns) \tag{6}$$

where f_{in} is the frequency of supply, slip is s, and n is an integer. It is shown as a effect of ripple in [29] demonstrates that the lower side band of frequency $f_{in}(1\text{–}2s)$ is the mightiest that may generate ripples in speed and torque at frequency of $2sf_{in}$, thus inducing an upper side band at a frequency of $f_{in}(1+2s)$ and this outcome will lead to continuation in creation of the above string of sideband frequencies $f_{in}\,(1 \pm 2ns)$. The lower sideband frequency $f_{in}(1\text{–}2s)$ above the fundamental one can be employed to monitor the rotor broken bar fault [30].

D. OTHER FAULTS

Eccentricity arises due to non uniform air-gap amidst the stator and rotor [28]. This may be generated by bearing defects or manufacturing failure. Extreme air gap eccentricity may commence inequitable radial forces and finally results in friction between stator and rotor, which may lead to severe damage to core of stator and rotor further causing breakdown of the motors. Eccentricity in induction machine may be categorized as static, dynamic as well as mixed air-gap [29]. Inherent static eccentricity is present in recently manufactured motors [31]. In static air gap eccentricity, location of minimum air gap radial length remains constant where as for dynamic air-gap eccentricity; it revolves with the speed of rotor. Static eccentricity and dynamic eccentricity concur in mixed eccentricity. Literature [30] illustrates that 10 percentage air-gap eccentricity maximum is allowed in induction machine. For medium voltage motors, as the air gap is comparatively lesser compared to motors of small size, a minute eccentricity may cause to an extreme motor failure. Thus in premature stage the recognition of eccentricity in air gap is requisite. In the presence of static as well as dynamic eccentricity, which do exists in practical applications, the current harmonics may be determined at the frequencies [31]–[34] as given by eq. 7 below:

$$f_{ef} = f\left[1 \pm m\left(\frac{1-s}{p/2}\right)\right] \tag{7}$$

where f_{ef} is the frequency related to eccentricity, f is the principal frequency, slip is s, m is an integer and p is the pole pairs.

III. CONDITION MONITORING TECHNIQUES

There is a challenging task for experts as well as researchers to analyze unhealthy induction motor performance and its analysis beneath abnormal condition. Therefore, numerous condition monitoring approaches have been recognized to identify the health of an induction machine. Various condition monitoring methods of induction machines have been discussed in subsequent sub-sections.

A. VIBRATION MONITORING

Vibration monitoring is usually used for detection of mechanical faults like mechanical imbalance or bearing faults [35]. The vibration in the stator frame is related to winding faults due to inter-turn failure, supply-voltage unbalance and single phasing. A piezo-electric sensor provides the voltage signal in proportion to acceleration which is frequently used. This signal can be used to measure the position or velocity. An absolute measurement is accomplished by seismic vibration sensors that are relative to free space [36]. The comparative vibration which is correlative to a stationary point usually limited to displacement measurement [37], [38].

B. MOTOR CURRENT SIGNATURE ANALYSIS (MCSA)

MCSA is an un-intrusive, online monitoring procedure for diagnosis of induction motor faults. In major applications current in stator winding is examined for diagnosis of various types of faults in induction motor [39]. It is also referred to as the predictive maintenance tool for the detection of induction motor failures at burn in stage which leads to non-occurrence of the catastrophic failures and hence induction motor life extends. The most popular techniques under MCSA are (i) current signature analysis (CSA), (ii) voltage signature analysis (VSA), (iii) extended Park's vector approach (EPPVA), and (iv) instantaneous power signature analysis (IPSA). MCSA is the process of getting signal like current and voltage of motor by carrying out signal conditioning. These voltage and current signals are acquired by a potential transformer (PT) and current transformer (CT). These acquired data are then examined by the advanced tools [40], [41] to extract more information from the captured signals. Numerous faults including core damages, loose wedges, defective bearings, foundation looseness, shots in inter turn, static eccentricity, damages in rotor bar as well as dynamic eccentricity are noticeable by MCSA technique without offensive the motor operation [42]. The faults which can be analyzed by MCSA are (i) static and / or dynamic air gap irregularities, (ii) broken rotor bar / cracked rotor end rings, (iii) stator faults (opening or shorting of one coil or more of a stator phase winding), (iv) abnormal connections of the stator windings, (v) bent shaft (akin to dynamic eccentricity) results in a friction between stator and rotor, causing severe harm to the core of the stator as well as its windings, and (vi) bearing and gearbox failures.

C. TORQUE MONITORING

In a rotating machine, torque is created by both the current as well as flux linkage is defined as air gap torque. Torque monitoring is used in cement, marine and power industries. This technique provides a clear understanding to the users when it is difficult to identify a problem through standard vibration analysis. Different kind of failures in induction machine produces harmonics that contains distinct frequencies in the air-gap torque. Rotor, shaft, and moreover mechanical loading on rotating machine maps to a spring system in analogous that has its unique inherent frequency, any attenuation in air – gap torque imparted through this spring system are distinct for distinct harmonic orders of components of torque. Air-gap torque which is delicate to any asymmetry created by faults as well as by unbalance in voltages in the supply system. Air-gap torque reflects specifically whether the unbalance is produced by cracked rotor bars or by stator unbalance linked with defects in winding and unbalanced voltages. Air-gap torque can be measured in the operating condition of the motor. This is majorly used in industries, where an unexpected motor down time leads to immense loss of production [43]–[45].

D. TEMPERATURE MONITORING

Electrical motor's thermal monitoring can be accomplished with the measurements of motor's local temperature. These can also be done by parameter estimation of the motor. In case of stator winding shorted turns of motor, the current in the stator will be tremendously high, and thus generates excessive heat, unless appropriate action is not taken in time can results into motor winding failure. Few researchers introduced the thermal model (Finite element analysis and Lumped parameter based model) of electrical machine. Finite element analysis is more appropriate than lumped parameter based model, but it is highly time consuming and has more computational burden [46], [47]. The lumped parameter based model which is analogous to thermal network and is comprised of capacitances, thermal resistances, and there relative power losses. In case of inter turn failure, the increase in temperature in the neighborhood zone of failure, but this might be very slow to determine the incipient failure before it propagates into a catastrophic failure [48], [49]. The temperature estimating methods have already been used for stator fault and bearing fault detection objective. This technique gives a meaningful sign of over-heating of the machine but this approach has limited fault analysis potential [50].

E. NOISE / ACOUSTIC NOISE MONITORING

Noise in electrical machines is due to the combination of sound signal which is generated by the fast changes in air pressure. These modifications generate most commonly: (i) Machine parts vibration on the whole surface of the machine (ii) Aerodynamic phenomena which leads to vibration of pressure near the motor. The prime sources of noise in induction motors are represented in Fig.7.

The spectrums of noise in induction motors are predominant by electromagnetic, acoustic noise and ventilation. Air turbulence produces ventilation noise. Periodic disturbance in air pressure is the cause of air turbulence. Air pressure is caused owing to rotating parts of induction machine. The electromagnetic noise is generated due to the influence of Maxwell's stresses acting on surfaces of the iron of the machine parts in the existence of the magnetic field. As a

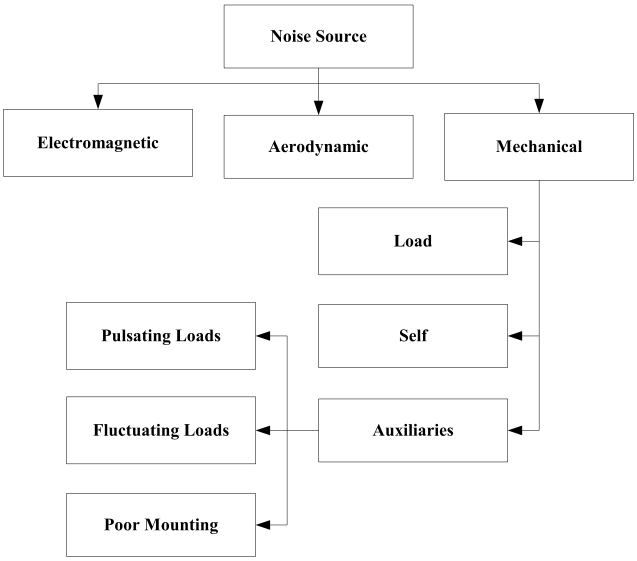

FIGURE 7. **Prime sources of noise in induction motors.**

matter of fact magnetic force produces vibrations in the structure of the stator, which leads to radiated noise. The sound level owing to mechanical and aerodynamic noise rise at a rate of twelve decibel per doubling the speed of the machine. Increased motor speed furnishes in growth of electromagnetic noise [51]. Inspection of the insulation of the ground wall is done by most appropriately embarking an ultrasonic wave upon the stator bar and utilizing the conductor like a waveguide [52]. Acoustic noise can be estimated by the noise monitoring from induction machine air-gap eccentricity. It is seen from the review of the literature that noise monitoring technique is less effective as in contrast to other monitoring approaches.

F. SPEED FLUCTUATION MONITORING

The speed fluctuations monitoring is a technique that can detect failure or defects using speed monitoring technique in the operational time span of the rotating machines. It is used for identification of faults in the rotor, vibration, air-gap eccentricity, asymmetries in rotor, damaged bearing etc. There are four types of sensor-less speed monitoring schemes which are (i) speed estimator, (ii) modal reference adaptive system, (iii) Luenberger speed observer, and (iv) Kalman filter technique [29]. In normal rotor bar, current fluctuates periodically in the form of sine wave with slip frequency, provide a contribution which will be developing the torque which will vary periodically in the form of sine wave with twice of slip frequency [53]. Shaft torque cannot be contributed by the defective rotor bar. For the rotor, the resulting torque can be divided into two components in which one is constant; another one varies with twice of the slip frequency. Mostly, the induction motor has variable load torque; the used instruments are capable of differentiating between load variations and variations of twice of the slip frequency showing rotor faults in induction motor [54].

G. INDUCED VOLTAGE MONITORING

The reasons of failures of rotating machines are (i) manufacturing tolerance (ii) origin in design (iii) assembly (iv) installation (v) working atmosphere (vi) schedule of maintenance (vii) nature of the load imposed on the rotating machine. Induction motor which is similar to other electrical rotating motors is also subjected to electromagnetic as well as mechanical forces [55]. So, the design and improvement of the induction machine leads to the interaction between these two forces under equilibrium states giving noiseless operation. While in the case of a fault, the equilibrium is lost that leads to further enhancement of the fault [56].

The voltage induced in healthy motor produces minimum noise/vibrations, whenever any failure or fault occurs in induction machine; the rotating motor shaft provides the information to the winding or stator core [57]. The induced rotor voltage parameter has not yet given significant results for condition monitoring due to its non-reliability and complexity.

H. SURGE TESTING

Winding failure can also be identified by surge testing technique. In this surge comparison test technique, two similar pulses of high voltage and frequency are concurrently applied on the winding of the two phases with third phase of the motor being grounded. An oscilloscope has been used for the indication of insulation failure between the windings, coils and group of the coils by comparing reflected pulses [63]. Pulse-pulse surge test method gives predictive information to identify the insulation deformation before the occurrence of turn-turn short circuit. The ''Surge Tester'' which is a handy and electronic piece of equipment used to find the insulation failure and dissymmetry of winding [58], [59], [62].

I. MAGNETIC FLUX MONITORING

The air-gap magnetic flux of an induction machine during healthy condition changes sinusoidally with time as well as space. If there is any occurrence of fault in rotor / stator, there may be variations in the air-gap flux [63]. The rotor faults can be identified by using a search coil which will be connected to the stator. The variations in the air-gap flux density which is caused by the stator or rotor produces a flux axially which can be investigated by a measuring coil around the rotating shaft either by other sensors [64]. The monitoring of the axial leakage of flux is probable to identify the different asymmetries and abnormalities such as related problems associated with stator inter-turn failure, eccentricity faults broken rotor bars, misalignment etc. [65].

J. PARTIAL DISCHARGE

Imperfection in insulation produces a little electrical discharge. Like delimitations within the insulation of the ground wall, resulting from excessive heating or poor manufacturing may lead to air pockets or voids, that may get discharged [66]–[72]. It is useful in recognition of the insulation problem in induction motor for precaution before the catastrophic failure occurs. This concept of PD involves material analysis, arcing characteristics, electrical fields, propagation of pulse wave as well as its attenuation, spatial sensor sensitivity, data and noise interpretation. The partial discharge analyzer (PDA) has evolved as the first technique which was used for the period of healthy machine (hydro generators) operation. Another method has been evolved by the use of dedicated sensors. The PD activity in a deteriorated winding has around thirty times or even more in comparison to a winding which is in healthy state. So PD is an incredibly beneficial practice to inspect the winding effectiveness as well as the motor health [73]. With online PD test [74]–[77] the stator winding effectiveness can be easily monitored. PD influences the motor which is a cause of long term degradation and failure of stator-rotor/electrical machine insulation. Rupture of stator winding insulation is one of the major causes of large sized IM rated 6 kV or above.

K. MOTOR CIRCUIT ANALYSIS

Motor circuit analysis by detecting the electro-magnetic behavior of the machine analogous to an electric circuit, identifies the fluctuations inside the motor as well as detects the faults. In this analysis a little quantity of energy with magnified outcome is imposed. The outcomes evaluate the state of the rotor as well as windings by the comparative observations [78]–[80].

L. GAS ANALYSIS

The carbon monoxide is produced owing to the degradation of electrical insulation which passes to the cooling circuit containing air in it. The carbon monoxide is detected by infrared absorption method [36]. The pulse width modulated pulses which are of high frequency generate too much peaks of the voltage that leads to the beginning of insulation breakdown of the motor. It happens due to electrostatic fields which are surrounded by opposite polarized electrical conductors, begins to strip electron from that neighboring air gap and leaves the positive charge generating ozone gas which reacts with the nitrogen present in air, further produces various forms of oxides of nitrogen. Nitrous oxide attacks the insulation of the winding that causes animosity and finally leading to fracture. The Ozone sniffing methods have been used for finding ozone [81]–[83].

IV. ADVANCED DIAGNOSTIC TECHNIQUES

The very fast evolution in the area of very-large-scale integrated (VLSI) design in addition with the development in the area of parallel computing architectures has rendered on-line digital signal processing (DSP) feasible for fault recognition in motor. The technique of digital signal processing habitually needed for the acquisition of sensor data and renovate rate for meticulous prediction of motor failures. This technique for diagnostics of faults is normally categorized as parametric, non parametric as well as high resolution spectrum investigation. Non-parametric approaches are the classical approaches that actuated by assessment the autocorrelation series of specific data, followed by the assessment of spectrum of the power by applying Fourier Transform. Similarly, the Fast Fourier Transform, which is an effective technique for computation, gives a conceptually easy method for induction machine current signature analysis [84]. In parametric approaches, a process model is specified by the enough preliminary knowledge and from these processed data, the model parameters are evaluated. Lastly by the use of these calculated parameters the power spectrum is then estimated. The autoregressive (AR), moving average (MA) as well as an autoregressive moving average (ARMA) models are persistent implementation for the presentation of the time series data. Since the parameters which are estimated are not significant it is efficacious to store or transmit rather signal values. This signal then reforms from the use of these parameters. There are numerous applications like cement industry processes, steel rolling mills etc., where the point of operation of the induction motor is oscillating. This leads to be an extremely dynamic signal like the voltage, current, voltage and power signals. The short time Fourier transforms (STFTs) has been used to process these non-stationary signals. STFT along with the pattern-recognition techniques has been accomplished for detecting the induction motor failures in such oscillating conditions. Simulation results reflect the methodology, best suited for discriminating multiple attribute of frequencies. CWT technique has been used to detect bearing fault in induction machine [85]. The main advantage of CWT is its applicability to extract information with high resolution and redundancy. In other words, scales of narrow range can be utilized to extract information from the band of a particular frequency. Very encouraging results are obtained with the scope of further applying this technique for recognition of other induction machine fault types. The support vector machine (SVM) is proven to be the best classification technique and this fact can be leveraged by using a hybrid CWT-SVM as a more efficient alternative to conventional classification techniques such as DWT/ANN. Wavelet analysis is another important technique for fault detection objective. STFTs have been used for analyzing signals which are non-stationary in a window of short signal as discussed earlier. In contrast to this in wavelet analysis non-stationary signals are concomitantly analyzed in time as well as in frequency domain at contrasting resolutions. STFT's application assumes the analysis to be pseudo stationary like speed of the motor and load on contrast to non-stationary signal. Precise detection of faults are associated with frequency has been accomplished by the use of finite impulse response (FIR) filter bank collectively with the spectrum of high-resolution exploration [86]. For estimating the dynamics of stationary signal large window has been utilized, on the other hand for transients smaller window has been used. This multi-resolution or multi scale view of the signal is the basis of the wavelet analysis [87]. Starting transient currents in induction machine have associated with the Non-stationary signals. Wavelet analysis by using the start-up transient current has proven its effectiveness for the fault detection at no load operation of the induction motor [88], [89]. Analytic wavelet transform (AWT) is an elegant algorithm which is capable of identifying and tracking the frequency of the faulted signal. The analytical wavelet ridge recognition [90] acquires the signal of small magnitude at the higher frequencies where the information of phasor from the AWT assists the tracking of the faulty signal of stator. Another effective technique is the combination of both wavelet as well as method of power-spectral-density, which is competent for recognition of failures such as rotor broken bar as well as eccentricity, occurs in an induction machine [91], [92]. The other diagnostic technique using wavelets, and signature of fault in frequency band inter relate with the frequency of supply, Time Synchronous Averaging (TSA) algorithm with DWT can give efficient result for detection of induction motor rotor faults [93].

V. MOTOR DIAGNOSTIC USING ARTIFICIAL INTELLIGENCE AND DEEP LEARNING

Induction motor incorporates the advantage of Neural Network, Fuzzy logic, combination of Neuro and Fuzzy and some optimization techniques like genetic algorithm, which are model free techniques. Thus, the incorporation of such algorithms in the system with mapping of input/output without many expressions of dynamics and control of the system is to be monitored. In [94] the detection of broken bar and eccentricity has been implemented by virtue of Artificial Neural Network (ANN). An ANN comprising of three layered back propagation architecture, trained by a Levenberg–Marquardt learning algorithm. The input signal to this network is filtered vibration signal. The trained neural network has been validated by using the known set of training data and residuals are obtained by using ANN output and the data to be monitored. Depending on set residual thresholds, triggering the indication of faults by means of these residues is obtained. The learning algorithms technique based on clustering with combination of ANN has been implemented. It has been shown in another technique, which is based on the behavior implement methods to have the assessment criterion in a similar manner based on clustering by means of K-means algorithm [95]. NN structure has been proposed in [96] for detection of bearing failure for induction motors connected with the grid. The suggested method examines the state in real time like voltage unbalance and torque varying condition. The proposed technique gives the effective result by the use of high-speed personal computer for experimental test in online mode. A novel technique has been demonstrated in [97] based on hybrid feature reduction technique, gives a remarkable processing of vibration signature which is obtained from the motor. The proposed method has been used to recognize the multiple failures in an induction machine by some sequential tasks i.e. signal decomposition, features estimation based on statistical time, by using genetic algorithm based feature optimization, integrating the principal component analysis, feature selection (by means of Fisher score analysis), feature extraction. The ANN based classifier has been used to identify the various types of failures. The effectiveness has been verified experimentally and the results have been compared with traditional reduction schemes, making the suggested methodology worthy for industrial applications. Authors have suggested ANN [98] based architecture for recognizing the induction motor failures in early stage. This proposed system comprises of feature extraction and classification within a single body system, has an ability to grasp the most appropriate features by the convenient training. The proposed method can also detect the electrical as well as mechanical failures with the aid of electrical quantity (current) and mechanical vibration signal. For combining the feature extraction and classification both, the authors have used 1-D CNN (convolution neural networks) for detecting the failures in a single learning framework. A deep learning based scheme have been demonstrated in [99] for online detection of bearing failure. The authors considered the practical failure occurrence, using the outer raceway scratch on the bearing. For characterization of the fault, a Convolution Neural Network (CNN) architecture is applied. Fast Fourier transform has been applied on the signature of the stator current, followed by training of the CNN with the aid of specific frequency component from feature extraction. The effectiveness of this scheme has been verified by experimental tests corresponding to different fault conditions of the bearing and has also been tested for detection of multiple failures. Similarly Self Organizing Map which incorporates radial basis function is implemented to visualize both electrical and mechanical faults at different operating speed. In this algorithm the RBF neuron with varying nature becomes an elegant to implement in a architecture in accordance with availability of input data which accomplishes the fault detection objective accurately along with its severity [100]. Similarly principal component analysis (PCA) [101] illustrates the feature selection scheme based on the dimensionality reduction. The efficacy of the method has been implemented in a test bed for introspection of bearing fault in induction motor. By virtue of implementation of PCA relevant features can be extracted for machine condition monitoring.

On the other hand fuzzy logic is also implemented for condition monitoring objective of induction motor. Adaptive neuro–fuzzy inference systems (ANFIS), wavelet fuzzy logic, wavelet packet transform (WPT), support vector machine (SVM) are some important intelligent algorithms which is more suitable in order to predict the motor failure. On contrary the growth model associated with the noise modeling manifests Markov model with higher order terms. Similarly fuzzy logic concatenated with wavelet techniques constitutes an important tool for health monitoring of induction motor. The rule based technique which is an important segment of fuzzy logic membership function has been implemented in order to investigate the condition monitoring. The dry bearing fault also occurs in induction motor due to in adequacy of the lubrication. Thus, the vibration signal randomly increases the probability of dry bearing fault on contrary to normal motor unless correctly analyzed. In this context the analysis of this vibration signal is carried out by means of wavelet transform [102] in order to augment the health of the motor in presence of dryness in bearing in the induction motor. Such analysis is carried out both in offline by virtue of C++ as well as online by MATLAB platform respectively. Similarly support vector machine (SVM) [103] for fault detection and classification objective for induction motor is explored by use of kernel function supplemented by wavelet for addressing multi-class classification. For training objective feature vectors are obtained from the current transient signal which is pre-processed with DWT PCA and kernel PCA. Fault detection objective for induction motor is analyzed by the initiation of transient signal associated with current that exploits the advantage of fusion of wavelet and decision tree in order to improve the accuracy [104]. WPT is the extended version of wavelet which uses the basis function and resolution both in time and frequency [105]. This can extract the signal feature retaining the characteristics of both stationary and non stationary signal. The obtained output from the WPT is applied with a combination of fuzzy logic in order to generate the feature vectors after normalization and storing the relevant pattern is obtained from the data from experimentation. The comparative assessment of the feature vector is carried out with real time data with that of the pattern being stored in the memory. Since WPT is a strong feature extraction technique, it has been incorporated with a combination of SVM in order to interpret the severity assessment, detection of fault and detection of composite fault with higher accuracy [106], [107]. Similarly the concept of WPT is implemented in [108] for stationary stator current in order to explore the different fault condition which has been verified in the experimental test bed. Deep belief network (DBN) which incorporates the model based on deep learning has been presented in [109], the input is data measured with frequency distribution for induction motor fault diagnosis in manufacturing. Restricted Boltzmann machine has been incorporated in the deep architecture, which uses the training based on greedy layer for the construction of the model. As a matter of fact, DBN becomes a strong candidate to model the data of higher dimension in multi layer learning representation. This approach has reduced the training error and improved the accuracy of classification. Experimental results interpret the efficacy of the model based on DBN, which provides the right direction of extraction of features for fault diagnostic in manufacturing industry. A novel method for nonlinear model of flux linkage of bearingless induction motors (BIM) have been proposed in [110]. For improving the accuracy of the flux linkage model, least square support vector machine (LSSVM) has been used with gray wolf optimization (GWO) technique. The relation between input and output of the proposed nonlinear flux linkage model has been studied, and precision model of GWO-LSSVM flux linkage have been obtained. Simulation results verify that the proposed model have its uniqueness including high accuracy as well as strong ability of prediction.

VI. CONCLUSION

The condition monitoring of induction motor as discussed in the previous sections in an elaborated manner has evoked the machine diagnostic procedure, analysis of data, communications, and management of information. Exploration of these techniques would make the right platform for engineers and researchers in order to get acquaintance in automated monitoring systems switched to diverse industry deployment circumstances which have not been earlier reported. In addition to the same comprehensive reviews of various faults, their causes, monitoring techniques, and development in premises, cloud, and internet of things of this in industrial automated systems are reported in this paper. The comprehensively reviewed methods and techniques would require further analysis for different technologies associated with the objective of security. As a matter of fact, the augmentation of the security would lead to minimum cost and deployment in large scale for future condition monitoring automation system of induction motors.

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