Condition Monitoring Techniques for Electrical Equipment—A Literature Survey

Y. Han and Y. H. Song

***Abstract*—Increasing interest has been seen in condition monitoring (CM) techniques for electrical equipment, mainly including transformer, generator, and induction motor in power plants, because CM has the potential to reduce operating costs, enhance the reliability of operation, and improve power supply and service to customers. Literatures are accumulated on developing intelligent CM systems with advanced practicability, sensitivity, reliability and automation. A literature survey is felt necessary with an aim to reflect the state of the art development in this important area. After introducing the concepts and functions of CM, this paper describes the popular monitoring methods for and research status of CM on transformer, generator, and induction motor, respectively. The paper also points out the potential benefits through the utilization of advanced signal processing and artificial intelligence techniques in developing novel CM schemes.**

***Index Terms*—Condition monitoring, generator, motor, transformer.**

I. Introduction

APPLICATIONS of condition monitoring (CM) into power station and development of new CM techniques have become one of the most important tasks for most energy companies since the beginning of 1990s. The need can be seen from two sides.

First, the health and safe operation of electrical equipment in power stations is so important that unexpected fault and shutdown may result in a great accident and get a high penalty in lost output cost, particularly under an ever-increasing competition environment. At the same time, the machines themselves are the expensive assets of the power stations and cost lot for maintenance. It is of no doubt that energy companies have to find some ways to avoid sudden breakdown, minimize downtime, reduce maintenance cost, and extend the lifetime of machines. CM is just the answer to these problems with the capability to provide useful information for utilising the machines in an optimal fashion. The coming of free competition in electricity business has made the application of CM not only necessary but also urgent.

Second, the development of computer technologies, transducer technologies, signal processing techniques together with artificial–intelligence (AI) techniques has made it possible to implement CM more effectively on electrical equipment. It is expected to make CM systems more reliable, more intelligent and cheaper, so that they can be widely employed in power systems.

However, CM is still under developing in a number of areas. Research works are now accumulated with great attention on sensitivity, reliability, automation with consideration of cost.

There are several general references [1]–[4] which are very useful, with information on CM of electrical rotating machines and transformers. This paper intends to provide an overall literature survey on this subject by describing the current research situation. However, it should be pointed out that there might be some papers missing due to the large number of publication in this area.

In the next section of this paper, the concept of CM is introduced. It presents the features and functions of CM, and related techniques so as to give a general picture of CM. Then, in Sections III–V, different CM techniques will be described and summarized for power transformer, generator and induction motor respectively. These form the main body of this paper. The highly concerned points are the common faults with related monitoring methods and recent research hotspots for each type of machines. Some comments and suggestion for further development will be made accordingly. At the last part of the paper, the development trends will be presented.

II. General Concept of Condition Monitoring

Condition monitoring can be defined as a technique or a process of monitoring the operating characteristics of machine in such a way that changes and trends of the monitored characteristics can be used to predict the need for maintenance before serious deterioration or breakdown occurs, and/or to estimate the machine's "health." It embraces the life mechanism of individual parts of or the whole equipment, the application and development of special purpose equipment, the means of acquiring the data and the analysis of that data to predict the trends [5]–[7].

CM is the technique served for Condition-Based Maintenance (CBM) (or named as predictive maintenance). Before this, time-based maintenance had been the mainly used maintenance strategy for a long time. Time-based maintenance, to examine and repair the machines offline either according to a time schedule or running hours, may prevent many failures. However, it may also cause many unnecessary shutdowns and unexpected accident will still occur in the intervals. Manpower and time and money were wasted because the activity of maintenance was blind with little information of the current condition of the machines. On the contrast, CBM will let operators know more about the state of machines and indicate

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The authors are with the Brunel Institute of Power Systems, Department of Electronics and Computer Engineering, Brunel University, London UB8 3PH, U.K.

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TABLE I
GENERAL ISSUES OF CONDITION MONITORING

TASK	PROCESS	MAIN TECHNIQUE	FEATURE	OUTPUT
What's the indication?	Data acquisition	Sensor, A/D, data communication	On-line, continuously or frequently	Raw data, or pre-processed, maybe contains noise
Does any defect exit?	Fault detection (by model-referenced method or feature extraction)	Neural network Signal processing etc.	Predictive	Warning, Compressed data
What's and where's the defect?	Pattern recognition, classification	Fuzzy logic, expert system, neural network, digital analysis, computer techniques etc.	On-line, automatic	Recognized defections, suggestion for maintenance, and other detail diagnostic result
What will be and what should be done?	State assessment, Assistant decision-making			

clearly when and what maintenance is needed so that it can reduce manpower consumption as well as guarantee that the running will never halt accidentally. CBM will be an optimal maintenance service under the help of a CM system to provide correct and useful information of the machine condition.

A CM system should be capable of monitoring the running machines with the existence of electrical interference, predicting the need for maintenance before serious deterioration or breakdown occurs, identifying and locating the defects in detail, and even estimating the life of machines. Four main parts should be contained in a CM system to practice these functions. They are as follows [1], [4].

1) *Sensor.* Sensors can convert a physical quantity to an electrical signal. Quantities and phenomenon will be monitored if they themselves or their detectable changes can reveal incipient faults long before catastrophic failures occur. Selection of sensors will rely on the monitoring method and come down to the knowledge on failure mechanisms of the machine. Commonly, the sensors should be suitable for on-line measurement. Sensitivity, cheapness, and noninvasion are the key requirements and expectation to practise this task.
2) *Data acquisition.* A data acquisition unit will be built to realize amplification and pre-processing of the output signals from sensors, for example, conversion from analogue to digital and correction of sensor failures. Data communication technique and microcomputer may be needed.
3) *Fault detection.* The main purpose is to find out if there is an incipient fault appearing in the machine so that alarm can be given and further analysis can be exerted. There are two deferent methods for fault detection, named model-referenced method and feature extraction. The former detects faults by comparing the results of measurements with predictions of models that may be mathematical simulation models or artificial intelligence based. For most feature extraction methods, frequency and time-domain signal processing technologies will be used to obtain 'signatures' which can represent normal and faulty performance.
4) *Diagnosis.* The detected abnormal signals need be post-processed to make out a prescription as a clear indication to maintenance. It used to be done by experts or offline analysis and now tends to be implemented online and automatically by computer combined with advanced technologies. The prescriptions presented to the user are expected to include name and location of each defect, status of the machine, advises for maintenance, and so on.

The tasks of CM, implementing process, and related technologies are summarized in Table I.

It is noticeable that the use of advanced signal processing and artificial intelligence technologies is attractive in this application as they are powerful in data analysis. As the functions of automatic interpretation and online diagnosis are considered more and more important in a CM system, modern condition monitoring can be named as Intelligent Condition Monitoring (ICM) with the features of fast calculation, intelligent analysis, and low cost.

III. POWER TRANSFORMER CONDITION MONITORING

A. Transformer Faults and Monitoring Techniques

The main components that ensure the normal operating of a transformer are the windings, core, main tank, cooler, oil, and On Load Tap Changer (OLTC). According to failure statistics [3], [8], OLTC failure and winding failure are the top two failures occurring in both station transformers and generator transformers. The key parameters that have to be monitored are the fault of OLTC, ageing of the oil/paper insulation (in both windings and the main transformer), and the load and operating condition.

1) Special Monitoring for OLTC: OLTC failures are dominated by faults of mechanical nature (springs, bearings, shafts, drive mechanisms), followed by electrical faults such as coking of contact, burning of transition resistors and insulation problems [3]. Components of a OLTC monitoring system are torque measurement and assessment of the motor drive, switching supervision, temperature measurement of the diverter switch oil, and a contact wear model in combination with measurement of load current [9].

Several systems for OLTC online monitoring are currently available [6], [10], [11]. However, integrated detector for mechanical and electrical faults is still expected. Vibration monitoring may be an effective method for online fault detection at a moderate cost [3]. Research on vibration monitoring methods for OLTC is under development and up to now few publications can be found.

2) Insulation Problem: Winding and main insulation is one of the biggest problems that affect the life of transformer. It can be indicated by temperature, gas-in-oil, partial discharge and moisture analysis.

Hot-spot temperature is always caused by overloading or local overheating. It is the limiting factor for the load capability of the transformer and has a big effect on transformer life via thermal aging behavior of insulation. The problem is that it is difficult to measure because of insulation problems. Using fiber optic temperature sensors seems the only way to get hot-spot temperature directly. However, it always costs a lot [3], [10]. The commonly used method is to calculate hot-spot temperature through thermal model with measurements of oil temperatures and of load current.

Gas in oil analysis is the traditional way to monitor insulation condition. Dissolved gases in the oil produced by thermal ageing can provide an early indication of an incipient fault. Gases normally analyzed are hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, ethane ethylene, and acetylene. Further analysis of concentrations, condition, and ratios of component gases can identify the reason for gas formation and indicate the necessity for further maintenance. Originally only a hydrogen online monitor was available but new instruments detecting several gases are commercially available with a total-oil monitor recently launched [3], [10].

All dielectric problems involve partial discharges in the initial stages of the failure process, so early detection of PD sources in the insulating system is very important. In transformers, the use of piezo-electric acoustic emission sensors attached to the transformer tank wall has been the approach most favored [12].

3) Other Monitoring-Worth Quantities: Voltages and currents are always monitored through traditional PTs and CTs as the basic information of load and operating condition. Vibration monitoring seems the strongest candidate for detecting OLTC failures. Another general practice mentioned in [13] is that vibration data are taken from both the core and windings of the monitored transformer via accelerometers and are used with current and thermal data to ascertain the online condition of the transformer.

B. Recent Research on Power Transformer Condition Monitoring

Some important work on power transformer condition monitoring, recently published in several major journals, is summarized in Table II, and it can be seen that the following four are main research areas.

1) Implementation of online monitoring system with accumulated successful experiences. Computer-based techniques are used for data processing, storage, and visualization. Several published CM systems are summarized in Table III.
2) Development of intelligent diagnostic system using fuzzy logic, expert system and neural networks. Although most of the up to date work is based on dissolved gas analysis (DGA) and for diagnosis of DGA result, AI techniques have the potential to be used for the whole diagnostic system with several types of sensor signals. Reference [13] showed the use of neural networks in both estimation and classification modes, based on vibration monitoring with assistance of current and thermal data.
3) Further research on partial discharge detection and location on running transformers. Elimination of electrical interference, calibration and location are the issues on the way of developing online PD monitoring.
4) Vibration monitoring for winding looseness [27] and OLTC failure. Online monitoring system for OLTC is still under developing.

IV. Power–Generator Condition Monitoring

A. Power–Generator Faults and Monitoring Methods

1) Stator-Winding Faults: Stator-winding faults may include insulation faults, winding subconductor faults and end winding faults. As majority of stator-windings fail as a result of gradual deterioration of the electrical insulation, insulation faults have always been a major concern. There are few incidents of failures due simply to ageing of insulation now. Failures due to isolated insulation defects do occur frequently, as a result of manufacturing defects, such as voids or foreign bodies, embedded in the main wall insulation, or penetration of the insulation by foreign material, such as oil or metal, from elsewhere in the machine [1]. The insulation breakdown leads to unbalance in the stator such as inter-turn faults, accompanied by changes in harmonic air-gap flux, current time harmonics and estimated equivalent turns.

The main early indication of stator-winding insulation faults is an increase in partial discharge activity in the machine, so that PD monitoring has been the main tool for implementing stator-winding CM for a long time. Through the interpretation of PD record, it is hopeful to get not only the health situation of the stator-winding, the location of PD source, but also the root causes of the defects, such as loose winding or conductive pollution.

2) Rotor Body Faults: Rotor body faults can be caused by high centrifugal stresses, large negative sequence current transients and eccentricity. The propagation of cracks from surface defects in the rotor material, or its associated components, due to high-cycle fatigue under the action of the self-weight forces during rotation, can lead to catastrophic rotor failure. Eddy current losses in the rotor due to the existence of negative sequence current can lead to overheating and the initiation of serious fatigue cracking. If a resonant condition exists between the generator and the system then sudden transient can excite torsional oscillations which can lead to rotor or coupling failure. Eccentricity of the rotor can lead to vibration due to unbalanced magnetic pull and this can be compounded when the asymmetric heating leads to thermal bending of the rotor [1].

The early indication of rotor body faults can be seen from vibration monitoring and air-gap flux monitoring [1], [30], [31].

3) Rotor Winding Faults: Older designs of rotor winding may suffer from insulation migration which leads to inter-turn shorts. Modern manufacturing techniques now involve preformed slot sections to prevent insulation migration, copper dusting and copper shortening where the windings move relative

TABLE II
LITERATURE SURVEY ON POWER TRANSFORMER CONDITION MONITORING

FAULT	MONITORING OBJECT & REASON	ON LINE MONITORING METHOD/ INSTRUMENT	RECENT RESEARCH PUBLISHED	NEW POINT AND/OR INVOLVED TECHNIQUE	COMMENT
WINDING INSULATION & MAIN INSULATION	**hot spot temperature** may affect the transformer life, limit the load capability	Traditional thermocouples, fiber optic sensor, thermal model, thermal image, infra-red (IR) thermography,	Winding temperature indicator [10]	Monitor and alarm	It cannot reliably represent the transient conditions
			Application of thermal model in monitoring system [14]	Model-based monitoring. Experience showed the existing IEEE thermal model doesn't handle transients of ambient temp. very well	
			Improved thermal model [9]	A modification is made on the IEEE model to adequately account for daily variations in ambient temperature	Reliability and sensitivity of monitoring need to be improved
	gas in oil a traditional way to monitor insulation condition; the types, concentration and production rates of generated gasses can be used for fault diagnosis.	Dissolved Gas-in-oil Analysis (DGA), Hydran sensor for detecting hydrogen, Furfural Analysis (FFA)	novel opto-electronic sensor for the determination of FFA [15]	On-site determine the concentration of FFA without need of experts	
			fluorescence-based measurement for the assessment of FFA [16]	A new measurement method	
			fault diagnosis for DGA intelligent decision support [17 - 22]	Fuzzy reasoning algorithm, expert system and artificial neural network	Intelligent diagnosis is now a research hot spot
	Partial Discharge (PD) symptom of all dielectric failure in the initial stages and cause of internal insulation damages	Radio Frequency Interference (RFI), Rogowski coil system, piezo-electric Acoustic Emission (AE), glass fiber rods acting as wave guides, detection of gas in oil	On-line PD calibration and monitoring [23]	Various methods are used to reject interference, an on-line calibration method is described.	On-line calibration is very important for on-line monitoring and diagnosis.
			Simulation model to study the propagation of PD pulses [24]	Simulation shows that, using the resonant frequency of the substation network as monitoring frequency, can increase the monitoring sensitivity.	EMTP is used to calculate an impedance matrix of a single-phase transformer
			PD source location based on AE [25]	AE instrument with three-dimensional source location software package	
			PD defection and location based on time encoded signal processing and recognition [26]	Analog-digital converters (ADC) and mathematical procedures for waveform description	
On Load Tap Changer (OLTC)	**OLTC** The majority of transformer failures are caused by tap changer fault	temperature monitoring of the diverter switch oil, contact wear model, torque measurement, tap changer position, vibration monitoring	Portable Open Circuit Indicator for OLTC [6].	Can detect an open circuit due to faulty or misaligned contacts in a star point OLTC	Vibration monitoring is the strongest candidate for detecting both mechanical and electrical faults of OLTC.
			Diverter Switch monitoring system and a Tapchanger Selector Switch monitoring system [11]	Monitoring the condition of the complete diverter switch and to detect if all the off circuit selector switch moving contacts are in their correct positions	

to each other during thermal expansion. However, shorted turns may still be a problem. It may be caused by copper dusts which cause arcing between the turns in the slot when the generator is rotating at a low speed during start up and shut down, or by great centrifugal forces and relatively high temperature affecting the winding and winding insulation. The fault may lead to local overheating and eventually to rotor earth faults. A popular monitoring method is air-gap magnetic flux monitoring [1], [32], [33]. Through air-gap flux probe, the result data can pinpoint the number and location (pole and coil) of shorted turns.

4) Stator–Core Faults: Stator core may suffer from large damaging currents following through the core bore which results as melting of core-plate steel. Modern cores on large machines are less massive than the older smaller machines and modern design techniques allow for closer tolerances and with the higher flux densities. However, there still is trouble for deep seated hot spots. Thermal monitoring techniques, including thermal image technique, thermal model and so on, have been used for power transformer and motor stator-winding monitoring. However, the practice on stator core monitoring is rarely reported.

TABLE III
SOME DEVELOPED ONLINE MONITORING SYSTEM FOR POWER TRANSFORMERS

Name & manufacturer	Monitoring quantity	Diagnostic function	Comment
MIT's model-based system [14]	Gas in oil, temperature	Giving identified cause and decision-making for maintenance	Thermal model is expected to improve.
Monitoring and diagnostic equipment, ABB [28]	Multiple gases, partial discharge levels, on-load tap changer performance, loading and key temperatures.	Off-line, DGA interpretation, PD location Prediction of OLTC failure by vibration analysis	Life expectancy assessment is mentioned. But no detail descriptions of the methods.
SIEMENS power transformer monitoring system [9]	Gas in oil, temperatures, voltages and currents, tap changer position, moisture, oil level, etc.	Giving alarm if some quantities are exceeding its limit	
ALSTOM MS2000 monitoring system [29]	Gas in oil, hot-spot temperature, cooling plant information, tap changer position and current, etc.	Giving alarm, visual measuring data, remote diagnosis	Using field bus technology for data communication

The majority of the recent papers, in the field of generator CM, have been contributed to PD online monitoring for stator-windings, which is summarized in the following section.

B. PD Online Condition Monitoring for Generator Stator-Windings

The deterioration of stator-winding insulation continues to be one of the main causes of large generator failures, and the majority of stator-windings fail as a result of gradual deterioration of the electrical insulation. So, PD monitoring system for stator-windings is one of the indispensable monitoring systems for generator maintenance. Study on PD monitoring has a long history of about 40 years, however, it is still an under developed technique. Some important work published recently is summarized in Table IV(1).

There are two main problems which need further attention. One is suppressing noises; the other is interpretation of PD patterns. More information on these two are described below.

1) Suppressing Noises: When stator-winding PD is online measured, it is usually obscured by electrical interference outside and/or inside the machine. Expert inspectors were necessary for this reason to discriminate stator-winding PD from noise, visually through oscilloscopes. It obviously limited the use of online PD monitoring. Efforts for suppressing noise inherently have been done through two ways. One is improving measurement means and instruments; the other is developing signal processing techniques and neural networks to eliminate noise from PD data in post-processing stage.

Among the companies and institutions which have been developing PD monitoring instruments, Ontario Hydro in Canada gives impressive series of products [40], [45], [49], [50], with more than 20 years of study. Partial Discharge Analyzer (PDA) was devised firstly for hydrogenerator, which inherently eliminated noise by a bridge-like pair of capacitive sensors which are permanently mounted on each phase of the machine. Then Turbine Generator Analyzer, with the use of a pair of capacitive couplers (bus couplers) mounted on each phase of the output bus (named TGA-B), developed for eliminating external noise for PD online monitoring on turbine generators. It automatically determines which pulses are due to PD from the stator-winding and obtains the magnitude, number, and phase position of such PD pulse as well. Stator Slot Coupler (SSC) is the newest developed instrument, for picking out internal and external noise existing in large turbine generators. SSC is a low voltage antenna installed in stator-winding slots containing stator bars connected to the phase terminals so that it can get the nearly real shape of stator-winding PD, which has the fastest rise time among all the pulses.

Signal processing techniques are the popular tools for suppressing noises. Electrical noises can be divided into narrow-band (continuous periodic) noises and broad-band (pulse-shaped) noises. The latter can be periodic or random with respect to power frequency. According to their frequency characteristics, various types of filtering method, such as adaptive digital filtering and program controlled band-pass filtering have been introduced [41], [44], [51]. Discrimination can also been done in time domain such as correlation between pulse height from the two PD sensors that used in [42].

Neural network algorithm also has been utilized to discriminate PD signals from noise signals. It can be based on PD pattern recognition or PD pulse phase distribution [46], [47]

2) Interpretation of PD Patterns: There are two results expected to infer form interpretation of online PD measurement [34], [40]. One is to identify which machines need stator-winding maintenance; the other is to find the location and root cause of any deterioration.

Experience has shown that detected PD magnitude is difficult to calibrate to be an absolute indication [39], so that a threshold is not enough for a decision of alarm. The condition of the stator-winding insulation had better to be identified via the trend over time or from comparing the results with similar machines, measured using the same methods [39]. The basic reason lies on distortion (resonance and attenuation) of PD signals propagating through windings, so that the possibility of reconstruction of original PD pulse and transfer functions are studied [43], [52].

There is a strong relationship between the shape of the PD patterns that occur in relationship to the power frequency sine wave and the type of defect causing them [34]. Some root causes of stator-winding deterioration can be identified through integrative analysis of the ratio of positive to negative PD magnitude and PD activity responded to change operation conditions [40]. Feature extraction and pattern recognition can be seen basing on ϕ-Q-N graph of PD [41]. Fractal image compression technique has been used for feature extraction [38], and neural network techniques have been used for pattern classification [17], [48].

TABLE IV
IMPORTANT WORK PUBLISHED RECENTLY ON PD ONLINE MONITORING (FOR GENERATOR STATOR WINDINGS)

AUTHOR / TIME	OBJECT / OBJECTIVE / FIND	INVOLVED TECHNOLOGY/INSTRUMENT/MAIN CONTENT	COMMENT
Gulski/99 [34]	Digital analysis of PDs	Rogowski coils and PD analyser, decision support database for diagnosis	Covering other high voltage components
Lloyd_BA/ 99 [35]	Automatic PD monitoring system for obtaining more interpretable data	Data acquisition unit, local area network, software written in C++	The newest monitoring system with function of configuring and control
McDermid /99 [36]	Experience and improvement of using directional couplers (bus couplers)	Directional couplers, compact 80 pF epoxy-mica capacitors	Confirmed the ability of suppressing noise
Zhu/99 [37]	Improve sensitivity of capacitive couplers	Using larger capacitance	Investigation
Lalitha/98 [38]	Fractal image compression for classification of PD sources	phi-q-n PD patterns, fractal image compression technique, affine transformations, neural network	General means for diagnosis
Stone/98a [39]	Calibration of PD measurements can't be done for motor and generator winding	pC and mV as PD measurement quantities, PD is symptom but not cause in some condition, Effect of winding characteristics on PD pulse, difficulty of calibration	Showing expert's opinion
Stone/98b [40]	Developed Canadian PD on-line measurement instrument for generators and motors, experience on interpretation of PD activity	PD analysis (PDA), Bus couplers with turbine generator analysis (TGA-B), MotorTrac for small motors, and stator slot coupler TGA-S for large turbogenerators	Introduction, a series of production for PD measurement
Wang_ZY/ 98 [41]	PD monitoring system with methods of suppressing noise and PD pattern recognition	CCU with HFCT and electromagnetic antenna, program controlled- attenuator, amplifier and band-pass filter for suppressing noise, surface fitting method for feature extraction, NN for pattern recognition	Overall description of PD monitoring system, containing diagnostic system and signal post-processing to cut noise
Itoh/96 [42]	To overcome the disadvantage of additional installation of sensors and for noise rejection	Using wires of a resistance temperature detector (RTD) as a PD sensor in the form of an RF coupler, noise rejection methods on pulse-by-pulse basis	
Kemp/96 [43]	Two possible calibration strategies	Identification of frequency band(s) where the PD pulse suffer minimal distortion; reconstruction of apparent PD pulse based on source location and transfer function	Investigation, Difficult to realize
Kopf/95 [44]	Rejection of narrow-band noise and repetitive pulses in on-site PD measurements	Digital FIR filter with a fixed order	
Stone/95 [45,46]	For diagnosis / PD occurred in unexpected portions of the phase, or unusual clumping (different from theory and lab experiment)	PD pulse analysis, TGA-SSC	Data accumulated through PD on-line monitoring in industry
Tanaka/95 [47]	PD pulse distribution pattern-analysis (from PD pulses on the voltage phase angle)	Statistical data analysis, neural network for noise discrimination and insulation diagnosis	
Satish/93 [48]	PD pattern-classification, automate diagnostic process	Multilayer neural networks	Some limitations were mentioned

V. INDUCTION MOTOR CONDITION MONITORING

A. Induction Motor Faults and Monitoring Methods

1) Stator Faults: Induction motor stator faults are mainly due to inter-turn winding faults caused by insulation breakdown, and it was showed in a survey that 37% of significant forced outages were found to have been caused by stator-windings [40].

Stator current signal analysis is now a popular tool to find out stator-winding faults [53]–[55], with the advantage of cheap cost, easy operation and multifunction. Fault conditions in induction motors cause the magnetic field in the airgap of the machine to be nonuniform. This results in harmonics in the stator current which can be signatures of several faults [56]. Beside the capability to detect turn-to-turn insulation faults, it can detect broken rotor bars, rotor eccentricity as well as mechanical faults on bearings [57]–[59].

As motors and generators have the similar problem in stator-windings, PD online monitoring on generators such as TGA-B can also be used to motors [40]. It has the merit of detecting winding faults earlier than current monitoring. However, it is more complex and only for insulation deterioration.

2) Rotor Faults: Induction motor rotor faults are mainly broken rotor bars as a result of pulsating load or direct on-line starting. It leads to torque pulsation, speed fluctuation, vibration, changes of the frequency component in the supply current and axial fields, combined with acoustic noise, overheating and arcing in the rotor and damaged rotor laminations.

TABLE V
RECENT WORK ON INDUCTION MOTOR CM BASED ON STATOR CURRENT MONITORING

AUTHOR / TIME	OBJECT / OBJECTIVE / FIND	INVOLVED TECHNOLOGY / INSTRUMENT / MAIN CONTENT	COMMENT
Benbouzid/ 99 [58,76]	To get easily distinguished spectral signature for detecting rotor eccentricity and broken bars, shaft speed oscillation, and bearings failure	High-resolution spectral analysis, including Eigenanalysis-based frequency estimators, MUltiple Signal Classification (MUSIC) and Root-MUSIC methods	Initial step for diagnostic purpose, Only voltage unbalance and stator open phase are proved
Nejjari/99 [77]	diagnosis of induction motor stator and phase conditions	fuzzy logic, fuzzy set theory	
Cardoso/99 [78]	On-line detection and location of inter-turn short circuits by non-invasive method	Stator current Park's Vector expression and patterns	Laboratory test, based on the appearance of elliptic patterns
Watson/99 [79]	Early detection of rotor faults	Finite element methods, including fixed mesh modelling and time step modelling, for simulating rotor faults	Transient simulation technique is being developed
Thomson/ 98 [80,81]	To find relationship between the severity of eccentricity and the magnitude of current spectra component	Time stepping finite element method for calculating EMF time domain waveform, FFT analysis technique, MATLAB	Developing new method for better diagnosis
Schoen/97 [56]	Removing arbitrary load effects from the current spectrum	Measuring three-phase current and voltage for estimation of the d-axis current of an ideal machine as a model reference value	Improving the detectability of current spectral
Schoen/95 [57,59]	Developing automatic diagnostic system [57]	Rule-based filter using expert system, neural network with clustering-type algorithms	Spectral characteristics of each machine must be learn first
	To find the relationship of the bearing vibration to the stator current spectrum [59]	Rolling-element bearing failure modes, Mathematical expression of harmonic frequencies related with different conditions	Initial research on efficacy of current monitoring for bearing

The most popular method for rotor fault detection is stator current monitoring as mentioned above. Other possible methods including vibration and air-gap monitoring [60], [61].

3) Bearing Faults: Motor reliability studies show that bearing problems account for over 40% of all machine failures, and rolling element bearings are overwhelmingly used in induction motors [59]. Incipient bearing faults are popular detected through vibration and stator current monitoring, and stator current monitoring has the advantage of noninvasion (requiring no sensors accessing to the motor).

4) Air-Gap Eccentricities: Air-gap eccentricity must be kept to an acceptable level, for example, 10% [62]. There are two types of air-gap eccentricities, static and dynamic. With static eccentricity the minimum air-gap position is fixed in space, while for the dynamic, the center of the rotor and the rotational center do not coincide, so that the minimum air gap rotates [1]. Unacceptable levels of them will occur after the motor has been running for a number of years. The air-gap eccentricity can be detected by using the stator core vibration and the stator current monitoring [1], [63].

B. Popular Monitoring Techniques and Recent Research for Induction Motor CM

1) Vibration Monitoring and Current Monitoring: There are many methods that can be used for induction motor CM; see [2]. Among them, vibration monitoring and current monitoring are the two most popular methods for practical application. Vibration monitoring has been put into practice [64], [65], while current monitoring is still under development. However, most of the recent research has been focused on the practice of current monitoring, which has showed potential to take the place of the status of vibration monitoring.

Vibration monitoring can indicate mechanical faults, uneven air-gap, stator-winding, or rotor faults, asymmetrical power supply, and so on. This is based on the fact that any change in the normal flux distribution in the motor will cause a change in the vibration spectrum. The measured or registered results, either the whole spectrum or certain frequency components are compared with that registered when the machine was new (or in a know condition) [2]. Improvement of vibration monitoring relies on advanced signal processing techniques, such as higher order statistics [60], [64], nonstationary recursive filters [66] and wavelet [67].

Current monitoring was thought difficult to detect a fault because of relative change in the supply current is small. However, this problem is being overcome [58]. It is now suggested that stator current monitoring can provide as much indications as vibration monitoring provided [2], [59]. A linear relationship between the current harmonics and vibration level is assumed in [68], for sensorless on-line vibration monitoring. Continuous research showed that a change in the rms value of the stator current is directly related to the change in vibration magnitude, for a known vibration frequency [69]. Some recent work is summarized in Table V, which shows the development of various detection and diagnosis techniques for induction motor faults by the help of advanced signal analysis and AI techniques.

2) Model-Based Method and Artificial Intelligence: Model-based fault detection can be seen as another class of CM techniques. Although not the mainstream of motor CM, they are considered more suitable and favorable for smaller motors and variable-speed drives.

A mathematical model of squirrel cage induction motor was built as a reference model in [70], then the deviations between the output of a measurement model and the reference model can be observed to detect and locate rotor faults. It showed the advantage of no need for frequency analysis so that it fits for variable-speed drive monitoring.

Neural network is alternative to mathematical functions for building models. When an accurate mathematical expression is difficult or even impossible to obtain for a nonlinear relationship, the reflection may sometime be easy to get via neural networks that can be trained by enough data. Examples can be seen in [55], [71], [72], where turn-to-turn insulation fault and bearing wear were detected through a trained neural network that reflects the relationship between (equivalent turns N, damping coefficient B) and the measured quantities—phase current and rotor speed. A series of work had then been done on training algorithm and knowledge extraction [73]–[75].

VI. Conclusion

Condition monitoring has become a very important technology in the field of electrical equipment maintenance, and has attracted more and more attention worldwide. The potential functions of failure prediction, defection identification, and life estimation bring a series of advantage for utility companies: reducing maintenance cost, lengthening equipment's life, enhancing safety of operators, minimizing accident and the severity of destruction, as well as improving power quality. Due to these benefits and the pressure to best utilize the existing assets under a competitive environment, CM is now a hot topic to power system managers and engineers as well as researchers.

The development of CM for power transformers, generators and induction motors is now at different stages. Several types of transformer monitoring systems have already put into practice. However, monitoring and data analysis methods are not satisfied for special problems such as partial discharge, hotspot temperature and OLTC. Online diagnosis of all the measured quantities is still under development. To large extent, CM systems for generator and induction motors are not practicable yet. Great efforts are focused on the use of PD online monitoring system for generators, while more work has been carried out on vibration signal analysis and the implementation of current monitoring.

Research in recent years clearly show that advanced signal processing techniques and artificial intelligence techniques are indispensable in developing novel CM systems. Benefiting from the development of computer techniques and communication techniques, signal processing and AI have become the most powerful tools to make next generation CM equipped with high level of sensitivity, reliability, intelligence, and cheapness.

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Y. Han is currently pursuing the Ph.D. degree at Brunel University, London, U.K.

Y. H. Song is Professor of electrical energy systems at Brunel University, London, U.K., where he also holds the Royal Academy of Engineering/Nuclear Electric/Siemens Chair of Power Systems.