Condition Monitoring Through Temperature, Vibration and Radio Frequency Emission: A Review

Abstract

Condition monitoring (CM) is an important topic for researchers dealing with electrical equipment and their performance. The condition and performance of electrical equipment can be monitored through analysis of their temperature, vibration or radio frequency (RF) emission. In the past decades, intensive research works have been conducted to study CM with the aim to improve reliability and performance of electrical systems and hence the state of art of this area is felt important to be reviewed. This paper reviews the most recent and popular approaches which intend to improve the CM performance through temperature, vibration, and RF emission methods. A brief overview on existing monitoring methods is presented and from the comparison between the existing methods, it is concluded that with proper analysis and reliable measurements, RF emission can present an excellent tool for monitoring electrical equipment. It is believed that this review would give the readers a good insight on various schemes and approaches of CM of electrical equipment.

Keywords: Condition monitoring, electrical equipment, temperature, RF emission, vibration analysis.

I. INTRODUCTION

Predicting failure of electrical equipment is a difficult task and attempting to prevent the outage requires locating where the fault is and how it is produced [1]. Electrical equipment are widely used in everyone's daily life and thus monitoring their performance has become essential for manufacturers and users [2]. To investigate the condition of electrical equipment, one needs to address the electromagnetic and dynamic behaviors of these systems. Maintenance, on the other hand, has become a serious issue for users and manufacturers of electrical equipment. It is important to find a convenient way for diagnosing equipment before a failure occurs. A preventive action is required to avoid hazardous faults from happening. Condition monitoring (CM) methods always aim to address the protection issue of electrical systems to ensure safety for societies and reliability of electrical equipment.

Many methods have been developed to diagnose the condition of electrical equipment based on their structures and states of operation. System variables like current, voltage, acoustic emissions and electromagnetic field (EMF) components that are emitted by electrical equipment can be used to make a decision on the condition of the equipment. When studying CM, it is essential to first locate the fault and then propose a solution to repair it bearing in mind that monitoring does not always suit all equipment due to technical and economic consideration of the system to be monitored [1, 3. 4]. An electrical test is then required to make a decision on the condition of the equipment. Such tests include temperature, vibration, RF emission, chemical, electrical analysis and other methods.

This paper attempts to review existing research contributions on CM of electrical equipment using temperature, vibration and RF emission monitoring methods. The paper presents existing approaches used for monitoring electrical equipment while discussing the challenges and difficulties which CM researchers are facing with the hope to point directions for new areas of research in this important field. Systemic summaries and brief comparisons are presented to allow readers identify advantages and disadvantages of every approach. The paper intends to classify existing approaches based on the way that problems were tackled. Researchers who are dealing with temperature, vibration, and RF emission and their relation with performance of electrical equipment will find this review a beneficial source of literature. For previous approaches and other methods that are not included in this review, readers may refer to [5-19] and therein references.

This paper is organized as follows: a brief introduction on the steps of CM of electrical equipment and currently used methods are presented in Section 2. In Section 3 selected recent and popular approaches of CM which have been proposed in this area during the recent two decades are reviewed. Section 4 presents a discussion and open issues of CM with a comparison between all the presented approaches of each monitoring method. Finally, Section 5 concludes the paper.

II. Overview on Condition Monitoring

Condition monitoring is defined as the process of monitoring the health condition of an electrical system to enable proper preventive maintenance to be carried out and avoid possible failures from occurring. One of the key steps of CM is the ability to predict the required maintenance at the right time.

As shown in Figure 1, there are five main steps involved to set up a CM system. The five steps are as follows [11], [20-21]: Sensing stage is the first step in designing a CM system. In this step one tries to find a sensing element for the purpose of monitoring one or more parts of the electrical equipment. This element should be chosen based on the method used for monitoring. Hence, it should be selected with consideration to improve the reliability, the cost, and the non-intrusive installation. The second step in designing a CM system is to consider a detection method where the targeted part of the equipment is sensed and monitored for any incipient fault in progress. There should be an indicator of any possible fault that can be detected using the sensor. Thirdly, the data acquisition should be considered where data is acquired and stored in a storage device and prepared for further analysis. Data acquisition may include certain software programs, programming language, and data conversion. Lastly, the analysis and diagnosis

The signals that are acquired through data acquisition are then analyzed. When abnormal patterns are detected, this indicates that the equipment under test has is experiencing an incipient fault and an action needs to be taken to rectify the malfunction.

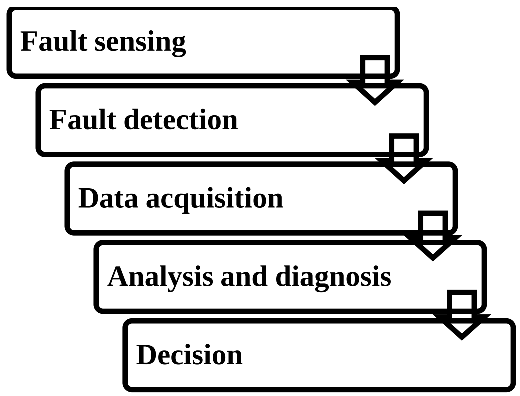

Figure 1: Basic Principle of CM

There are many approaches of CM in the literature. These approaches are classified based on the methods used for monitoring. Some researchers focus on temperature based monitoring such as the study on thermocouple detectors by [22] and [23] as well as other temperature based monitoring techniques including fiber optics, infrared thermography, and thermal condition monitoring [24-28]. Other researchers concentrated on the vibration based monitoring methods including the use of vibration and acoustic emission data as seen in [36-47]. On the other hand, there are researchers who concentrated on RF emission analysis for monitoring electrical system using RF data generated by operating electrical equipment [29-35]. These are the major methods that have been intensively studied in the recent two decades. However, there are other methods such as chemical monitoring and oil-based monitoring methods that have been studied by other researchers [48-52]. The following section will briefly introduce the monitoring methods that will be discussed throughout this paper.

Temperature is considered one of the earliest methods of electrical equipment CM and fault detection. The use of temperature monitoring can provide sufficient information about equipment failure in many industrial systems and processes. By using a temperature detector, it is easy to localize the spot where a piece of equipment is experiencing a high level of temperature. There are different types of temperature detectors' designs such as thermocouple detectors described in [22]. Other types of detectors are described in [23]. Recently, there is a good development in the optic-fiber based sensor which is described in [24].

Thermography analysis, on the other hand, has been used recently, for instance, those described in [2] and [42]. The importance of temperature based CM approach lies in its direct indication of the operating electrical equipment where a certain value of the temperature could represent a sign of fault.

On the other hand, in some of the electrical systems, misalignment, unbalance, resonance, electrical machine structure problems, and other electrical machine faults can be detected using vibration analysis. Recently there have been several approaches that address the use of vibration analysis to diagnose a fault in electrical equipment and machines.

According to [2] there are four main sources of vibration. The first source of vibration is the stator response to the force between rotor and stator. The second source of the vibration comes as the electrical machine rotates. It generates a dynamic change in the bearings. Thirdly, the vibration can be recorded as the shaft bearing responses to the vibration of the rotor. Lastly, a vibration can be spotted from the stator especially as a response to the electromagnetic forces on the conductors. Acoustic emission is one of the vibration parameters used for monitoring electrical systems and has been introduced in many approaches to diagnosing the operating equipment [41-46].

A. RF emission monitoring

RF emission is radiated from electrical equipment due to the fact that equipment may be operated by one or more motors which can be a source of emission. However, the radiated emission is produced mostly by the windings, inverters and supply cables [42]. Experiments have shown that this radiation has a frequency range of 1-50 MHz in most of electrical equipment [42]. Electrical equipment emit unique RF emission during their operation [32]. This emission is a noise signal that can cause interference to sensitive systems nearby.

III. Condition monitoring approaches

All presented approaches in this paper are grouped with respect to the monitoring method used. The selection of each approach is considered for the contribution towards a useful and integrated CM system that can be able to monitor electrical equipment, detect faults and present suitable solutions.

A. Temperature based monitoring approaches

Temperature based monitoring can be of two types namely; local and hotspot measurement with thermal image analysis. Guo et.al [53] introduced a method for monitoring the wind turbine generators. This approach is based on modeling the normal behavior of electrical generators temperature with the use of nonlinear state estimation technique (NSET). Data collection process is performed using supervisory control and data acquisition (SCADA). This approach proves a good prediction accuracy and simplicity of computation. However, the implementation of this approach is a bit difficult especially when it comes to data collection and processing

Another approach to temperature-based monitoring is introduced by Guo, et. al [54] for monitoring the condition of wind turbine gearbox using Auto-associative Kernel Regression (AAKR). Like the approach discussed in [53], SCADA was used for data collection and AAKR which is claimed to be non-parametric, empirical modeling technique that utilizes previously recorded data with fault-free observations to estimate the output of a process or a device. However, this approach lacks real failure data since the data used are man-made failure data. The approach needs to be tested using a real failure data to prove its usefulness for such measurements and predictions.

Sangeetha, M. S., et al. Developed a methmeatical model to describe the relation between hotspot temperature, emissivity and distance. IR data from different equipment were recorded and used to build the model. By using these relations, the actual temperature can be calculated to detect any anomalities.

Another temperature-based approach is introduced by Sheiretov et.al [56]. In this approach, the high-temperature components in power plants are monitored. They deployed sensors to measure the temperature and employed an algorithm for predicting failures. This approach is good for monitoring equipment that experience high temperature because the maximum temperature being monitored reached 850 Celsius degrees.

In [57], N. Baker et al. suggested that the junction temperature in power semiconductor devices can be experimentally calculated instead of being estimated with the use of the provided manufacturer datasheets. The implementation of real time monitoring, however, needs further research as it has not been made yet.

Work by [58] introduced infrared thermography based condition monitoring of electrical equipment. In this approach, neural networks (NN) classification system was introduced. Three sets of features namely first-order histogram based statistical, grey level co-occurrence matrix and component-based intensity features are extracted by image analysis, which is then used as input data for the neural networks. The conditions of electrical equipment were classified accurately and authors suggest that the results was achieved using perceptron network.

Another infrared thermography technology, which uses the artificial neural network (ANN), has been developed in [59]. In this approach the performance of each feature was studied individually to achieved the best feature set. However, it is seen from the results of the experiment that there is room for improving the accuracy of the classifier where only 74% accuracy was achieved.

Work by [60] presented a new intelligent diagnosis method for classification different conditions of electrical equipment using data obtained from infrared images. The statistical features that can help in identifying the temperature reading were extracted from each region of interest. Features were then combined and fed as input to the SVM. 97.8% accuracy was achieved using this technique which is consider a significant improvement.

The work reported in [61] discussed a new method for hot spot indication technique and also presented transformer’s operating condition which is monitored by using a thermal imaging. From the thermal analysis, it was suggested that hotspots are usually identified from the connection. Also it is pointed out that the busing of the transformer is the hottest spot in the transformer.

Table 1 shows the main points of each temperature-based approach where the problem and solution proposed by each approach, performance metrics, diagnostic tools and comments on each approach are highlighted.

TABLE 1: TEMPERATURE BASED MONITORING TECHNIQUES

Approach	Problem	Solution	Performance Metrics	Diagnostic Tools	Comment
Wind Turbine Generator Condition Monitoring Using Temperature Trend Analysis [53]	High maintenance costs caused by wind turbine generator faults. Fault prediction accuracy need to be improved.	The use of non-linear state estimation along with moving average filter for prediction of faults at early stages.	Prediction Accuracy and model robustness	Temperature SCADA System	This method presents faster prediction, however, authors didn't explain the mechanism of adding values for the second turbine to give failure indication.
Wind Turbine Gearbox Condition Monitoring with AAKR and Moving Window Statistic Methods[54]		Auto-associative Kernel Regression (AAKR) is used to construct the normal behavior model of the gearbox temperature	Simplicity of computation		The approach lacks experimenting real failure data instead of man-made gearbox failure data.
Mathematical Relationship Between Hotspot Temperature, Emissivity and Distance in Thermographs for Condition Monitoring of Electrical Equipments [55]	Variation on the environment temperature creates confusion on fault detection	A mathematical model is derived to relate the emissivity to the hotspots of temperature and image processing is used to analyze this relation.	Accuracy	IR images	Though this work present good analysis, data collection and database volume were not clearly explained.
MWM-Array Sensors for In Situ Monitoring of High-Temperature Components in Power Plants [56]	Material degradation,	Design of sensors, coupled with multivariate inverse methods, to provide superior performance for in situ material CM	Reliability & Broad applicability	HT-MWM and HT-MWM-Array Sensors	A good maximum temperature measurement reached 850 Celsius degree
Junction Temperature Measurements via Thermo-Sensitive Electrical Parameters and their Application to Condition Monitoring and Active Thermal Control of Power Converters [57]	Junction temperature is calculated using estimation methods along with datasheets provided by manufacturers	Suggestion to use TSEPs for CM is provided instead of depending on the calculated values of the junction temperature which is always dedicated for the worst case scenario.	Reliability improvement	Thermo-sensitive electrical parameters (TSEP)	Implementation of real time monitoring using this technique is yet to be researched.
Suitable Features Selection for Monitoring Thermal Condition of Electrical Equipment using Infrared Thermography [58]	Manual analysis of thermal image takes a lot of time	Introduce infrared thermography based condition monitoring	Reliability and stability	Multilayered perception network	The best features are selected by using a Levenberg-Marquardt algorithm
A New Thermographic NDT for Condition Monitoring of Electrical Components using ANN with Confidence Level Analysis [59]	Faults in electrical systems	By infrared thermography technology to predictive faults diagnosis	Most effective non-destructive	Thermal image, Neural Network	This technology gives better accuracy and sensitivity
A Novel Intelligent Fault Diagnosis Method for Electrical Equipment using Infrared Thermography [60]	Difficulties to find the region of interest	New intelligent diagnosis method is proposed	Accuracy	K-means algorithm, support vector machine (SVM)	This approach gives a good performance and accuracy
A Real-Time Study on Condition Monitoring of Distributors Transformer using Thermal Image [61]	Maintenance cost caused by transformer outage	Transformer's operating condition is monitored by using a thermal imager	Accuracy and real-time power quality analysis	Thermal Imager	A real-time measured data has been made

B. Vibration-based monitoring approaches

The measurement of periodic process of machinery oscillations is used for monitoring the electrical equipment and a high level of this acoustic noise can indicate a failure. As mentioned in the earlier sections, many approaches have been proposed using this type of measurements. For instance, Iorgulescu. M et. al [62] attempted to diagnose electrical equipment using vibration monitoring. They focused on the transformer as the equipment under test and analyzed the vibration signals from the piezoelectric accelerometer that they attached to the equipment. Then, they applied the FFT to the signal and compared the results from both healthy and faulty equipment. The results of their approach showed significant increasing on the vibration signal amplitude of the faulty transformer in comparison to the healthy one.

Gupta et.al [63] introduced a fiber optic vibration sensor to monitor the health of electrical equipment. This design shows an easy setup and claimed to guarantee a good monitoring process. However, this study lacks validation on a real measurement data of electrical equipment fault sensing.

Another approach for identifying the equipment failure root causes was proposed by Bakar et.al [64]. Three different approaches are combined namely; ultrasound, transient earth voltage (TEV) and infrared Thermoscanning. However, this approach is categorized under vibration methods because the ultrasound method is claimed to achieve the highest percentage of the correct identification of actual root causes. The advantage of this work is that it is carried out with condition-based monitoring data that have been recorded sufficiently. However, it is suggested that author could explain how the assumed value of the decibel is chosen.

Ahmad Kh et.al [65] introduced an approach for investigating Outer Race Fault (ORF) of electrical equipment using statistical analysis on recorded vibration data. The time domain signal is studied along with statistical measures and gives promising results towards achieving ORF vibration sensing. This approach indicates that the number of parameters to be chosen is suggested to be more than two for better prediction of the faults. Results show that increasing load will result in an increment in the standard deviation value and the range of cumulative distribution as well. Although this method gives promising results, it is suggested to try selecting combined statistical features to see if further improvement on fault detection can be achieved.

Later, Muñoz et.al [66] presented a diagnosis tool based on vibration and acoustic emission. Experimental setup includes motoring tests for determining the vibration behavior to distinguish mechanical events from combustion-related ones. Pattern recognition and identification of the fault included a comparison between recorded signals of a faulty engine and the signals obtained for the engine under normal working conditions. This approach is considered efficient because it was validated after repairing the faulty part of the equipment and because it was used to diagnose the emergency diesel generator (EDG) in the nuclear power plant and is claimed to be reliable on real diagnosis basis. Table 2 shows the main points of each approach.

TABLE 2: VIBRATION BASED MONITORING TECHNIQUES

Approach	Problem	Solution	Performance Metrics	Diagnostic Tools	Comment
Vibration monitoring for diagnosis of electrical equipment's faults. [62]	Faults in transformers and AC/DC motors	Using FFT to compare the vibration amplitude of healthy and non-healthy equipment's	Signal frequencies variation from different tests	Piezoelectric accelerometer	Results need to be validated and or compared with previous approaches if any
Vibration sensor for health monitoring of electrical machines in power station [63]	EMI influnce in detecting machine vibration	The fiber optic vibration sensor is introduced.	Compactness Reliability & Cost Reduction	Sensor	Design steps are clear. However, the sensor needs to be tested in the real environment to prove its applicability
Identification of failure root causes using condition-based monitoring data on 33kV switchgear [64]	CBM unable to identify the root cause of failure .	The use of ultrasound and TEV to obtain CBM data to be process	Effectiveness Reliability Cost effective	Ultrasound, Transient earth voltage (TEV) and Infrared thermo-scanning	Need to on improve TEV method and clarify the assumption of choosing decibel value
Experimental Investigations on Outer Race Fault in Ball Bearings of Electrical Machines Using Statistical Analysis [65]	Bearing outer race fault identification	Time domain data signals are used along with statistical measures to identify faults.	The accuracy of detection.	LabView and machine analyzer MK-500	This approach is considered to be effective and further improvement on choosing features is possible
Engine diagnosis method based on vibration and acoustic emission energy [66]	Complicated ways to determine engine faults	Using the vibration and acoustic emission energy data and compare it with the reference.	Reliability, accuracy Cost	A single-cylinder engine for the test and acoustic emission sensors with LABVIEW software	The approach is validated well and is considered efficient.

C. RF emission based approaches

By studying the radiated signal, one can predict and detect any faulty component from operating equipment. Lauletta, John L [67] introduced a device to sense the location of an arc source for the aim of locating failing equipment of a system. The system senses a frequency range of 1MHz–1GHz. EXACTER® Outage-Avoidance System is used in this study which is made up of a mobile sensor to be planted in an aircraft or a vehicle, a mobile network to transmit data and a Web Information Portal for accessing the findings of the field. This study provides a complete system and measurements which can be used for detecting various failing equipment of any intending electrical system.

Shihab et.al [68] introduced an approach for detecting the faulty components in power lines. Based on the RF pulses (as a monitoring parameter) radiated by the faulty component. RF pulses were captured using a biconical antenna which has a frequency range of 20MHz to 300MHz. The analysis includes statistical analysis and estimation accompanied by wavelet. The comparison is then made, and results show that although RF signals have distinctive features compared to other conditions, there are several conditions which frequency signals are similar in term of voltage level, time period and signal pattern in the time domain. This may result in more error if the number of fault conditions increases. This study lacks covering monitoring lower frequency range that may be found in power lines and other electric systems.

The partial discharge was investigated by Moore et.al [69]. This approach includes the localization of partial discharge in the transformer by moving an antenna array around the transformer at different step distances. The bearing of the source of the partial discharge from the array is calculated and then the correct pulse radiation is identified. Although this approach is limited to detecting radiation source with relatively high pulse signals, this study presents a good method of identifying emission source that can be enhanced for better results. In Table 3, the main features of each RF emission based approach are highlighted.

Work by [70] proposed the use of Blind Source Separation (BSS) techniques applied to pairs of UHF sensors to extract the information of the difference of the time of arrival of the electromagnetic pulses radiated by a source of PD. This approach is focused on the application of the algorithm and the description of an experimental setup for controlled generation and detection of PD to verify the performance of the proposed technique. The technique of BSS gives feasible and versatile way to find the time difference between the signals.

Another cost-effective approach by [71] is to develop a non-invasive, area-wide monitoring system that, from a distance, can collect signals emitted from a variety of electrical and mechanical equipment and perform data analysis that can reveal potential anomalies or provide an early indication of developing malfunctions. Sensing changes in the acoustic and electromagnetic (AEM) signatures of equipment using sensors that monitor sound pressure (acoustic signature) and electromagnetic data (electromagnetic signature) can be incorporated at a particular angle and distance from the equipment to trend changes in equipment performance, and indicate a potential failure. This approach is simple, cost-effective, and can survey a large area for the purpose of improving equipment reliability.

The aim of the approach [72] is to present a new prospective method for on-line monitoring of partial discharge (PD) in large AC motors. The principle of this system consists to measure the weak magnetic high-frequency field, due to PD, in the space between the magnetic core and the machine external frame of large generators. Special sensors, trimmed to the machine winding resonances, may perform such field measurements. With several sensors, it will be possible to localize PD activity corresponding to insulation weaknesses.

TABLE 3: RF EMISSION BASED MONITORING APPROACHES

Approach	Problem	Solution	Performance Metrics	Diagnostic Tools	Freq. range	Comment
A Novel Sensing Device for Power System Equipment Condition monitoring [67]	Locating failing equipment	The use of RF emissions along with GPS to pinpoint failure in the electric grid	Effective Accuracy	HF detectors, filters, an omnidirectional wideband antenna, a computer, GPS and data-communication equipment	0.001-1 GHz	An efficient measurement and failure identification was demonstrated
Detection of Faulty Components on Power Lines Using Radio Frequency signature and signal processing Techniques [68]	Faulty components increase in power lines	RF emission based monitoring with a suggestion on remedy actions	Ease of implementati on	Biconical antenna and signal processing	20-300 MHZ	The approach needs to be improved especially when a number of faults increases.
Partial Discharge Investigation of a Power Transformer Using Wireless Wideband Radio-Frequency Measurements [69]	Partial discharge (P D) detection	Use of mobile wideband radio-frequency receiving equipment for detection	Ease of measuremen ts	Mobile wideband RF receiving equipment.	Unspecifi ed	This method is suitable when the objective is to find the emission source which can help identifying fault location in an RF-based CM system
Location of Partial Discharges Sources by Means of Blind Source Separation of UHF Signals[70]	Interfering signals when measuring electromagn etic pulses	The use of blind source separation (BSS) techniques applied to pairs of UHF sensors	The effective time difference of arrival	Monopole antenna, UHF sensors, high-frequency current transformer	5GHZ	The technique of BSS give feasible and versatile way to find the time difference between the signals
Area Acoustic and Electromagnetic Emissions Monitoring of 3-Phase Motors[71]	Due to an equipment malfunction in an electric power plant may be difficult and costly	Develop a non-invasive area-wide monitoring system	Provide an early indication of developing malfunctions	Acoustic and Electromagnetic Sensors System	Unspecifi ed	This method is able to identify the loading condition.

Prospective Method for Partial Discharge Detection in Large AC Machine using Magnetic Sensors in Low Electric Field Zones[72]	Weak magnetic high-frequency field due to Partial Discharge (PD)	New prospective method for on-line monitoring of PD in large AC motors	Ease to localize PD activity	Stator laminated core, machine frame	1-5 MHZ	This method is able to detect PD in large AC motors

IV. DISCUSSION AND OPPORTUNITIES

From the approaches discussed above, it is noticed that temperature based monitoring method presents reliable information about the condition of electrical equipment. This is due to the relation of the heat to the operation status of equipment. Improving these methods can lead to the better early identification of the equipment failure especially when it comes to the use of non-intrusive sensors as well as the thermography approaches that show a good indication of equipment deterioration. However, sometimes the sensors being used in temperature based methods must be located inside or very close to the tested equipment and hence may give a wrong reading and could be damaged due to excessive heat in certain cases.

Vibration and acoustic emission are found to be very good indicators of the electrical equipment deterioration and have become of wide use in CM systems in the recent years. The literature shows good approaches in this field and acoustic emission proves its applicability to predict failures in many of the equipment especially the rotating machinery. Even though vibration analysis presents some complex analysis, it is proved to provide reliable and accurate fault prediction tools.

RF emission method provides non-intrusive fault detectors and with proper analysis and reliable measurements, this method can present an excellent tool for monitoring electrical equipment. The recorded signal of RF emission can be analyzed through its pattern, magnitude, and frequency range to identify an existing failure or predict its happening. It is suggested for researchers dealing with RF emission and EMF to consider electric field (EF) strength that can be captured from equipment and other radiation sources. By using an appropriate probe, the EF can be measured and recorded signals can be further analyzed and may give some indication of the health condition of various equipment.

V. CONCLUSIONS AND RECOMMENDATIONS

This paper has provided a survey of temperature, vibration and acoustic and radio frequency methods used in CM systems. From the review, it can be concluded that vibration and acoustic emission have become of wide use in CM systems in the recent years mainly because there are many types of vibration and acoustic sources that can be chosen from. The temperature-based CM approach needs a direct indication of the operating electrical equipment where a certain value of the temperature could represent a sign of fault. On the other hand, the radio frequency emission can be a non-intrusive fault detector and with proper analysis and reliable measurements, it can be a future trend of a tool for monitoring electrical equipment. Future researchers on CM using the radio frequency may consider concentrating on improving prediction, identification of failures and providing early remedies and avoidances intelligently and non-intrusively.

VI. ACKNOWLEDGMENT

The authors are grateful to the Malaysian Ministry of Higher Education (MOHE) for the financial support given through the Exploratory Research Grant Scheme (ERGS).

VII. REFERENCES

[1] Liu, X. T., F. Z. Feng, and A. W. Si. "Condition based monitoring, diagnosis and maintenance of operating equipment of a hydraulic generator unit." IOP Conference Series: Earth and Environmental Science. Vol. 15. No. 4. IOP Publishing, 2012.

[2] Tavner, Peter, et al. Condition monitoring of rotating electrical machines. Vol. 56. The Institution of Engineering and Technology, 2008.

[3] Sugarman, A. "Condition monitoring of electrical equipment in nuclear power plants." Energy Conversion, IEEE Transactions on 3 (1986): 1-8.

[4] Su, Stephen YH, and Yun-Chung Cho. "A new approach to the fault location of combinational circuits." Computers, IEEE Transactions on 100, no. 1 (1972): 21-30.

[5] Nandi, Subhasis, and Hamid A. Toliyat. "Condition monitoring and fault diagnosis of electrical machines-a review." Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE. Vol. 1. IEEE, 1999.

[6] García Márquez, Fausto Pedro, et al. "Condition monitoring of wind turbines: Techniques and methods." Renewable Energy (2012).

[7] Mehrjou, Mohammad Rezazadeh, et al. "Rotor fault condition monitoring techniques for squirrel-cage induction machine—A review." Mechanical Systems and Signal Processing 25.8 (2011): 2827-2848.

[8] Hameed, Z., et al. "Condition monitoring and fault detection of wind turbines and related algorithms: A review." Renewable and Sustainable energy reviews 13.1 (2009): 1-39.

[9] Tavner, P. J. "Review of condition monitoring of rotating electrical machines." Electric Power Applications, IET 2.4 (2008): 215-247.

[10] Wang, M., A. J. Vandermaar, and K. D. Srivastava. "Review of condition assessment of power transformers in service." Electrical Insulation Magazine, IEEE 18.6 (2002): 12-25.

[11] Han, Y., and Y. H. Song. "Condition monitoring techniques for electrical equipment-a literature survey." Power Delivery, IEEE Transactions on 18.1 (2003): 4-13.

[12] Afzal, M. H., Shahid Kabir, and Othman Sidek. "An in-depth review: Structural health monitoring using fiber optic sensor." IETE Technical Review 29.2 (2012): 105.

[13] Zhang, Yingwei. "Process monitoring, fault diagnosis and quality prediction methods based on the multivariate statistical techniques." IETE Technical Review 27.5 (2010): 406.

[14] Peng, Z. K., and F. L. Chu. "Application of the wavelet transform in machine condition monitoring and fault diagnostics: a review with bibliography." Mechanical systems and signal processing 18.2 (2004): 199-221.

[15] Kurada, S., and C. Bradley. "A review of machine vision sensors for tool condition monitoring." Computers in Industry 34.1 (1997): 55-72.

[16] Rehorn, Adam G., Jin Jiang, and Peter E. Orban. "State-of-the-art methods and results in tool condition monitoring: a review." The International Journal of Advanced Manufacturing Technology 26.7-8 (2005): 693-710.

[17] Jardine, Andrew KS, Daming Lin, and Dragan Banjevic. "A review on machinery diagnostics and prognostics implementing condition-based maintenance." Mechanical systems and signal processing 20.7 (2006): 1483-1510.

[18] El Hachemi Benbouzid, Mohamed. "A review of induction motors signature analysis as a medium for faults detection." Industrial Electronics, IEEE Transactions on 47.5 (2000): 984-993.`

[19] Jemielniak, Krzysztof, et al. "Tool condition monitoring based on numerous signal features." The International Journal of Advanced Manufacturing Technology 59.1-4 (2012): 73-81.

[20] Tavner, Peter J., and James Penman. Condition monitoring of electrical machines. Letchworth: Research Studies Press, 1987.

[21] Grimmelius, Hugo T., et al. "Three state-of-the-art methods for condition monitoring." Industrial Electronics, IEEE Transactions on 46.2 (1999): 407-416.

[22] Milanovic, Veljko, Micheal Gaitan, and Mona E. Zaghloul. "Micromachined thermocouple microwave detector in CMOS technology." Circuits and Systems, 1996., IEEE 39th Midwest symposium on. Vol. 1. IEEE, 1996.

[23] Brown, Colin, et al. "On generalisation of dual-thermocouple sensor characterisation to RTDs." MELECON 2010-2010 15th IEEE Mediterranean Electrotechnical Conference. IEEE, 2010.

[24] van de Giesen, Nick, et al. "Double-ended calibration of fiber-optic raman spectra distributed temperature sensing data." Sensors 12.5 (2012): 5471-5485.

[25] Picazo-Rodenas, M. J., et al. "Use of infrared thermography for computation of heating curves and preliminary failure detection in induction motors." Electrical Machines (ICEM), 2012 XXth International Conference on. IEEE, 2012.

[26] Wong, Wai-Kit, et al. "Thermal condition monitoring system using log-polar mapping, quaternion correlation and max-product fuzzy neural network classification." Neurocomputing 74.1 (2010): 164-177.

[27] Ahmed, N., et al. "Condition monitoring in the management of maintenance in a large scale precision CNC machining manufacturing facility." Condition Monitoring and Diagnosis (CMD), 2012 International Conference on. IEEE, 2012.

[28] Cardoso, Francisco JA, Sergio PS Faria, and Jose EG Oliveira. "A smart sensor for the condition monitoring of industrial rotating machinery." Sensors, 2012 IEEE. IEEE, 2012.

[29] Judd, Martin D., Li Yang, and Ian BB Hunter. "Partial discharge monitoring of power transformers using UHF sensors. Part I: sensors and signal interpretation." Electrical Insulation Magazine, IEEE 21.2 (2005): 5-14.

[30] An, Fu Wan, Li Si Hua, and Wang Chang You. "On-line partial discharge measurement for insulation condition monitoring of HV cables." Instrumentation & Measurement, Sensor Network and Automation (IMSNA), 2012 International Symposium on. Vol. 1. IEEE, 2012.

[31] Stone, G. C. "Partial discharge diagnostics and electrical equipment insulation condition assessment." Dielectrics and Electrical Insulation, IEEE Transactions on 12.5 (2005): 891-904.

[32] Alkahtani, Ammar Ahmed, et al. "Analysis on RF emission of electrical appliances." Control System, Computing and Engineering (ICCSCE), 2012 IEEE International Conference on. IEEE, 2012.

[33] Strachan, S. M., et al. "Knowledge-based diagnosis of partial discharges in power transformers." Dielectrics and Electrical Insulation, IEEE Transactions on 15.1 (2008): 259-268.

[34] Muhr, M., and R. Schwarz. "Partial discharge measurement as a diagnostic tool for HV-Equipments." Properties and applications of Dielectric Materials, 2006. 8th International Conference on. IEEE, 2006.

[35] Cusido, Jordi, et al. "Fault detection in induction machines using power spectral density in wavelet decomposition." Industrial Electronics, IEEE Transactions on 55.2 (2008): 633-643.

[36] Kim, Yeon Whan, Ju-Young Ho, and Young Shin Lee. "Development of Vibration Condition Monitoring System Applying Optical Sensors for Generator Winding Integrity of Power Utilities." International Journal of Modern Physics: Conference Series. Vol. 6. World Scientific Publishing Company, 2012.

[37] Sanders, Colin. "Maintenance managers guide to...: Vibration analysis and associated techniques in condition monitoring." Asset Management & Maintenance Journal 25.1 (2012): 30.

[38] Siegel, David, et al. "A comparative study on vibration-based condition monitoring algorithms for wind turbine drive trains." Wind Energy (2013).

[39] Bartelmus, W., and R. Zimroz. "Vibration condition monitoring of planetary gearbox under varying external load." Mechanical Systems and Signal Processing 23.1 (2009): 246-257.

[40] Watson, Simon Jonathan, et al. "Condition monitoring of the power output of wind turbine generators using wavelets." Energy Conversion, IEEE Transactions on 25.3 (2010): 715-721.

[41] Loutas, T. H., et al. "The combined use of vibration, acoustic emission and oil debris on-line monitoring towards a more effective condition monitoring of rotating machinery." Mechanical systems and signal processing 25.4 (2011): 1339-1352.

[42] Mba, David, and Raj BKN Rao. "Development of Acoustic Emission Technology for Condition Monitoring and Diagnosis of Rotating Machines; Bearings, Pumps, Gearboxes, Engines and Rotating Structures." (2006).

[43] Kosaraju, Satyanarayana, Venu Gopal Anne, and Bangaru Babu Popuri. "Online tool condition monitoring in turning titanium (grade 5) using acoustic emission: modeling." The International Journal of Advanced Manufacturing Technology (2012): 1-8.

[44] Pai, Srinivasa, T. N. Nagabhushana, and Raj BKN Rao. "Tool Condition Monitoring Using Acoustic Emission, Surface Roughness And Growing Cell Structures Neural Network." Machining Science And Technology 16.4 (2012): 653-676.

[45] Lee, Dae-Eun, et al. "Precision manufacturing process monitoring with acoustic emission." International Journal of Machine Tools and Manufacture 46.2 (2006): 176-188.

[46] Sun, J., et al. "Identification of feature set for effective tool condition monitoring by acoustic emission sensing." International journal of production research 42.5 (2004): 901-918.

[47] Doughty, Richard L., and Austin H. Bonnett. "Introduction to IEEE 841-2001, IEEE standard for petroleum and chemical industry-severe duty totally enclosed fan-cooled (TEFC) squirrel cage induction motors-up to and including 370 kW (500 HP)." Petroleum and Chemical Industry Conference, 2001. IEEE Industry Applications Society 48th Annual. IEEE, 2001.

[48] Macian, V., et al. "Analytical approach to wear rate determination for internal combustion engine condition monitoring based on oil analysis." Tribology International 36.10 (2003): 771-776.

[49] Newell, Gary E. "Oil analysis cost-effective machine condition monitoring technique." Industrial Lubrication and tribology 51.3 (1999): 119-124.

[50] Xie, Xiaopeng, Wei Feng, and Qiansheng Liao. "Study on Condition Monitoring in Petrochemical Equipment Using Oil Analysis Technology." Advanced Tribology. Springer Berlin Heidelberg, 2010. 942-946.

[51] Wang, Wenbin, B. Hussin, and Tim Jefferis. "A case study of condition based maintenance modelling based upon the oil analysis data of marine diesel engines using stochastic filtering." International Journal of Production Economics 136.1 (2012): 84-92.

[52] Jiang, Xu Feng, Fang Liu, and Peng Cheng Zhao. "Failure Analysis of Rolling Bearing Based on Oil Monitoring Techniques with Mechanics Basis." Applied Mechanics and Materials 164 (2012): 401-404.

[53] Guo, Peng, David Infield, and Xiyun Yang. "Wind turbine generator condition-monitoring using temperature trend analysis." Sustainable Energy, IEEE Transactions on 3.1 (2012): 124-133.

[54] Guo, Peng, and Nan Bai. "Wind Turbine Gearbox Condition Monitoring with AAKR and Moving Window Statistic Methods." Energies 4.11 (2011): 2077-2093.

[55] angeetha, M. S., et al. "Mathematical Relationship Between Hotspot Temperature, Emissivity and Distance in Thermographs for Condition Monitoring of Electrical Equipments." 2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI). IEEE, 2018.

[56] Sheiretov, Yanko, et al. "MWM-array sensors for in situ monitoring of high-temperature components in power plants." Institute of Electrical and Electronics Engineers, 2009.

[57] N. Baker, M. Liserre, L. Dupont, and Y. Avenas, "Junction temperature measurements via thermo-sensitive electrical parameters and their application to condition monitoring and active thermal control of power converters," *IECON 2013 - 39th Annu. Conf. IEEE Ind. Electron. Soc.*, pp. 942–948, 2013.

[58] A. S. N. Huda and S. Taib, "Suitable features selection for monitoring thermal condition of electrical equipment using infrared thermography," *Infrared Phys. Technol.*, vol. 61, pp. 184–191, 2013.

[59] A. S. N. Huda, S. Taib, K. H. Ghazali, and M. S. Jadin, "A new thermographic NDT for condition monitoring of electrical components using ANN with confidence level analysis," *ISA Trans.*, vol. 53, no. 3, pp. 717–724, 2014.

[60] H. Zou and F. Huang, "A novel intelligent fault diagnosis method for electrical equipment using infrared thermography," *Infrared Phys. Technol.*, vol. 73, pp. 29–35, 2015.

[61] T. Mariprasath and V. Kirubakaran, "A real time study on condition monitoring of distribution transformer using thermal imager," Infrared Phys. Technol., vol. 90, pp. 78–86, 2018.

[62] Iorgulescu, M., Beloiu, R., & Popescu, M. O. (2010, May). Vibration monitoring for diagnosis of electrical equipment's faults. In Optimization of Electrical and Electronic Equipment (OPTIM), 2010 12th International Conference on (pp. 493-499). IEEE.

[63] Gupta, Neha, and Sakshi Pahuja. "Vibration Sensor For Health Monitoring Of Electrical Machines In Power Station." International Journal of Engineering Science 4 (2012).

[64] Bakar, A. H. A., et al. "Identification of failure root causes using condition based monitoring data on a 33kV switchgear." International Journal of Electrical Power & Energy Systems 47 (2013): 305-312.

[65] Ahmad, K. H., S. P. Gupta, and Vinod Kumar. "Experimental Investigations on Outer Race Fault in Ball Bearings of Electrical Machines Using Statistical Analysis." IETE Journal of Research 58.2 (2012): 96..

[66] Muñoz, M., et al. "Engine diagnosis method based on vibration and acoustic emission energy." Insight-Non-Destructive Testing and Condition Monitoring 54.3 (2012): 149-154.

[67] Lauletta, John L. "A novel sensing device for power system equipment condition monitoring." Transmission and Distribution Construction, Operation and Live-Line Maintenance (ESMO), 2011 IEEE PES 12th International Conference on. IEEE, 2011.

[68] Shihab, S., and K. L. Wong. "Detection of faulty components on power lines using radio frequency signatures and signal processing techniques." Power Engineering Society Winter Meeting, 2000. IEEE. Vol. 4. IEEE, 2000.

[69] Moore, Philip J., Iliana E. Portugues, and Ian A. Glover. "Partial discharge investigation of a power transformer using wireless wideband radio-frequency measurements." Power Delivery, IEEE Transactions on 21.1 (2006): 528-530.

[70] C. Boya, M. V. Rojas-Moreno, M. Ruiz-Llata, and G. Robles, "Location of partial discharges sources by means of blind source separation of UHF signals," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 4, pp. 2302–2310, 2015.

[71] A. F. Browne, S. Patel, S. A. Kaloti, S. M. Lopez, and P. Parikh, "Area acoustic and electromagnetic emissions monitoring of 3-phase motors," *2017 IEEE Int. Electr. Mach. Drives Conf. IEMDC 2017*, pp. 3–8, 2017.

[72] S. Ait-Amar and D. Rogera, "Prospective method for partial discharge detection in large AC machines using magnetic sensors in low electric field zones," in *IET 8th International Conference on Computation in Electromagnetics (CEM 2011)*, 2011, pp. 1–2.