A Methodical Review of Condition Monitoring Techniques
For Electrical Equipment

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Abstract: Condition monitoring has a great potential for enhancement in the reliability of operation, machine up-time, reduction in consequential damage and improving operational efficiency at lower operational cost. In electrical equipment incipient faults are often characterized by variations in temperature, vibro-acoustic signature, etc. Different condition monitoring techniques use dedicated sensing and data analysis tools to analyze particular type of variation in operational characteristics. Research in this domain is primarily focussed on specific use of a sensing technology. However, this work is aimed to act as a guide for an industrial or academic user to choose the right technique for condition based maintenance of their equipment and to present a comprehensive review of prevalent condition monitoring technologies, i.e. Vibration signal analysis, Acoustic emission testing, Ultrasound condition monitoring, Infrared thermography and lubrication oil analysis. A detailed review of condition monitoring techniques which can be used to detect a particular type of fault is presented with an aim to identify the most suitable technique for fault diagnosis.

Keywords: Infrared thermography, Acoustic Emission, Vibration Analysis, Ultrasound, Lubrication oil analysis, Condition Monitoring

Introduction
Condition monitoring is a process of continuously monitoring operational characteristics of a machine to predict the need for maintenance before a deterioration or breakdown occurs. Condition Based Maintenance (CBM) differs from earlier used method of preventive maintenance by centering the maintenance based on the actual condition of the machine rather than on some preset schedule. The need of condition monitoring arises from the fact that in a power plant or a power utility any unexpected fault or a shutdown may result in a fatal accident or huge loss of output. Condition monitoring solves these problems by providing useful information for utilizing the machines in an optimal fashion. The recent development in computer and transducer technologies coupled with the advances in signal processing and artificial–intelligence (AI) techniques has made it possible to implement CBM more effectively on electrical equipment making it a more reliable and intelligent approach which can be used at various levels of power generation and distribution. This study shall present a review of various condition monitoring techniques for electrical equipment.

Vibration signature analysis
Vibration is a cyclic or pulsating motion of a machine or machine component from its point of rest[1]. Vibration of a machine can be represented in time domain in terms of its phase and amplitude (which can be measured as displacement, velocity or acceleration), and in frequency domain by its dominant frequencies, harmonics, etc. Vibration signature analysis (VSA) is a widely used condition monitoring technique to determine the overall condition of a machine, which is based on measurement of vibration severity of the machine under test. Every machine in its working condition produces vibration and this vibration is a characteristic signature of the machine which does not change over time. However, in cases of structural or functional anomaly or failure, the dynamic characteristics of the machine changes
which is reflected in its vibration signals[2]. The nature of the developing fault has unique vibration characteristics which can be compared with the vibration signatures of the machine working under normal operating condition. By using various signal analysis techniques one can determine the exact category/type of fault.

**Signal analysis:** Vibration signals encountered in rotary machine systems, such as machine tools, wind turbines or electric motors can be broadly classified as stationary or non-stationary. Stationary signals are characterized by time-invariant statistic properties like periodic vibrations caused by a worn out bearing etc. Such signals can be adequately analyzed using spectral techniques based on the Fourier Transform[3]. In contrast, non-stationary signals are transient in nature, with duration generally shorter than the observation interval. Such signals are generally generated by the sudden breakage of a drilling bit, flaking of the raceway of a rolling bearing, or a growing crack inside a work piece. For analysis of such non-stationary vibration signals, time-frequency techniques like Short-Time Fourier Transform for fault detection during impulse testing of power transformers (STFT)[4], wavelet transform[5] and Hilbert-Huang Transform (HHT)[2] are popularly used.

**Acoustic emission testing**

Acoustic Emission Testing (AET) is a condition monitoring technique that is used to analyze emitted sound waves caused by defects or discontinuities. These acoustic emissions (AE) are transient elastic waves induced from a rapid release of strain energy caused by small deformations, corrosion or cracking, which occur prior to structure failure. In electric machines sources of AE include impacting, cyclic fatigue, friction, turbulence, material loss, cavitations, leakage, etc.[6][7]. These acoustic emissions propagate on the surface of the material as Rayleigh waves[6] and the displacement of these waves is measured by AE sensors which are almost always a piezoelectric crystal, commonly made from a ceramic such as lead zirconatetitanate (PZT)[8].

**Data acquisition and analysis:** For the purpose of data acquisition sensors are placed on the material surface, the information collected by each of the sensors is monitored. If defects exist in some areas, the signal characteristics from the sensor attached nearest to the discontinuity appears in different way. By analyzing the discontinuity, it is possible to ascertain the defect position and suspect area of the structure. Broadly the data analysis can be done by two approaches. The first one is parameter based approach which is based on the analysis of basic signal parameters such as the rate, energy and amplitudes etc. [9]. In parameter based analysis only some of the parameters of the AE signal are recorded, but the signal itself is not recorded, this minimizes the amount of data stored and enables faster analysis. However sometimes these parameters lose massive information which makes characterizing of defects very difficult[10]. The other approach is waveform analysis technique which is based on the complete waveform rather than on the parameters. The waveform based approach offer better data interpretation capability than parameter based approach by allowing the use of signal processing methods like Wavelet-based acoustic emission characterization [11], second generation wavelet transform[12], wavelet envelopment spectrum analysis [10] etc. and also provides better noise discrimination[13].

**Ultrasound condition monitoring**

Ultrasound is defined as “sound waves having a frequency above the limits of human hearing, or in excess of 20,000 cycles per second”[14]. Many physical events cause sound at audible and/or ultrasonic frequencies, analysis of these frequencies can frequently indicate correct or incorrect operation[15]. Ultrasonic condition monitoring (UCM) is a technique that uses airborne(non-contact) and structure borne(contact) ultrasound instruments to receive high frequency ultrasonic emissions produced by operating equipment, electrical emissions and leaks etc. to monitor the condition of equipment under test[16]. Ultrasound transducers electronically translate ultrasound frequencies through a process called heterodyning, down to the audible range while maintaining the sound quality during the transition. These signals are observed at intensity and/or dB levels for analysis.
**Active and passive ultrasound monitoring techniques:** In passive techniques ultrasound detected by airborne or structure borne instruments is produced by a physical process i.e. by the component being analyzed. Passive ultrasound is used mainly for contact methods of monitoring such as bearing faults, lubrication issues, gear damage and pump cavitations[14] and non-contact methods of monitoring like leaks in boilers, condensers, and heat exchangers[17], electrical discharge and corona in high voltage equipment[15] etc. Airborne ultrasound detects high frequency sound produced by mechanical equipment, electrical discharges and most leakages which is extremely short wave in nature. These short wave signal tends to be fairly directional and localized which make them very easy to separate from background plant noises and to detect their exact location[16]. On the other hand active ultrasound is an approach where a precisely guided beam of ultrasound is transmitted to a physical structure to analyze both surface and subsurface discontinuities like delaminations, disbonds, cracks and porosity at early stages. The guided wave interacts with the structural discontinuity which causes reflection from a particular depth in material or scattering of guided waves in all directions, both results in transmission loss. These transmission losses can be detected by mapping the transmitted signal over the whole structure, known as a Through-transmission C-scan[18]. From various characteristics of the received ultrasonic signal, such as the time of flight, amplitude, frequency content, etc., the information about the depth of the damage is assessed [19][20].

**Infrared thermography**

Temperature is one of the most common indicators of the structural and functional health of equipment and components. Faulty machineries, corroded electrical connections, damaged material components, etc., can cause abnormal temperature distribution[21].Infrared thermography(IRT) is the process of using thermal imagers to capture infrared radiations emitted by an object to locate any abnormal heat pattern or thermal anomaly which indicate possible fault, defects or inefficiencies within a system or machine asset[22]. The basic principle underlying this technique is based upon Planck’s law and Stefan-Boltzmann’s law which states that all objects with temperature above 0 K (i.e. -273°C) emits electromagnetic radiation in the infrared region of electromagnetic spectrum i.e. wavelength in the range of 0.75–1000 µm[23] and the intensity of this IR radiation is a function of temperature of body.Infrared thermography is generally classified in two categories, passive and active thermography [1].In passive thermography, the temperature gradients are naturally present in the materials and structures under test. However in some cases the thermal gradient is not so prominent in case of deeper and smaller defects and is not visible on the surface using passive thermography. This is overcome by the use of active thermography where the relevant thermal contrasts are induced by an external stimulus[24]. Passive thermography is mainly applied for condition monitoring of electrical and mechanical equipment[25], whereas active method has been widely applied in areas such as medicine, thermal efficiency survey of buildings, agriculture and biology, detection of gas leak etc.

**Condition monitoring of machine using IRT:** Condition monitoring of an electrical machine using IRT is a technique that relies majorly on temperature measurement of the equipment under test. There are two approaches for temperature measurement. The first one is quantitative, in which the exact temperature values of the objects are considered with ambient temperature as reference. The second approach is qualitative, in which the relative temperature values of a hotspot with respect to other parts of the equipment with similar conditions are considered [25]. Qualitative analysis require a great understanding of variables influencing radiometric measurement including object’s emissivity, transmissivity, reflectivity, atmospheric conditions and machine[23]. In qualitative analysis there is no need to have a finer knowledge about variables influencing the temperature measurement. However, this method fails to perform correctly when a fault occurs in all similar components or a systematic failure occurs affecting all three phases, it also does not provide information about whether the equipment temperature limits are actually exceeded [10].

In terms of analysis condition monitoring of a machine using IRT can be done by two methods i.e. manual and automatic. In manual method a thermographer proposes potential faults and anomalies by
manually analyzing the thermal images of equipment under test. In automated method of inspection artificial intelligence techniques use acquired temperature information as well as information available from previous tests to generate results. Automatic condition monitoring of machine in a broader view can be categorized as a three step process. The first step involves acquisition of infrared images(s) of the machine under test. The second step involves extracting the region of interest (ROI) containing the potentially faulty portion of the machine using techniques likes image segmentation [5], thresholding[26]. Finding ROI plays a very crucial role in IRT as the key success of decision making process depends on the correct ROI detection. The relevant information like $T_{\text{min}}$, $T_{\text{max}}$, $T_{\text{avg}}$ and temperature gradient etc. are extracted from ROI and passed on to classifiers for final fault classification. The final stage of classification uses the extracted current features and compares them with a prior created database using advance learning methods like artificial neural networks(ANN)[7], support vector machine (SVM)[26] and fuzzy based decision making[27], etc.

**Lubrication oil analysis**

Lubrication oil is used in electrical and mechanical machines to reduce friction between moving surfaces. The lubrication oil is important source of information for early machine failure detection. In comparison with vibration based machine health monitoring techniques, lubrication oil condition monitoring can provide approximately 10 times earlier warnings for machine malfunction and failure[28]. Lubrication oil analysis (LOA) includes fluid property analysis (fluid viscosity, additive level, oxidation properties and specific gravity), fluid contamination analysis (moisture, metallic particles, coolant and air) and wear debris analysis[29]. Fluid property and contamination analysis is used to analyze the condition of oil to determine whether the oil itself has deteriorated to such a degree that it is no longer suitable to fulfill its primary function of reducing friction and preventing wear. Wear debris analysis is a technique which is used to monitor equipment’s operating condition (health) by analyzing the content of debris in the lubrication and hydraulic oil samples[30]. For all these techniques methods like particle filtering [28], spectrographic oil analysis[31], Analytical ferrography[32] and Radioactive tracer methods[33] etc. are used to study the chemical composition of oil. However, it is an offline analysis requiring the sample to be taken from the machine and tested in laboratory.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>FAILURE</th>
<th>IRT</th>
<th>UCM</th>
<th>VSA</th>
<th>AET</th>
<th>LOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor bar</td>
<td>Broken bar</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Transformer</td>
<td>Loose connection, Insulation defect, Lack of oil, Dampness</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Bearing</td>
<td>Bearing wear</td>
<td>[40][41]</td>
<td>[15][42]</td>
<td>[3][43][44]</td>
<td>[45][46][47]</td>
<td>[48]</td>
</tr>
<tr>
<td>Surge arrester</td>
<td>Surge arrester failure</td>
<td>[27]</td>
<td></td>
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<tr>
<td>Steam pipes</td>
<td>Leaks in steam cycle</td>
<td>[49][50][51]</td>
<td>[52][17]</td>
<td>[53]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV equipment</td>
<td>Corona, Electric discharge</td>
<td>[49][54]</td>
<td>[52][55]</td>
<td></td>
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<tr>
<td>Wind turbine blades</td>
<td>Structural defects</td>
<td>[20]</td>
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<tr>
<td>Wind turbine/ gear train</td>
<td>Gearbox failure</td>
<td>[56]</td>
<td>[57][58][59][60]</td>
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<td></td>
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<tr>
<td>Pumps/ hydro turbines</td>
<td>Cavitations</td>
<td>[17]</td>
<td>[61]</td>
<td></td>
<td>[7][61]</td>
<td></td>
</tr>
<tr>
<td>Pipes</td>
<td>Cavitations, Erosion, Wall thinning</td>
<td>[62]</td>
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</tbody>
</table>

**Table 1: Condition Monitoring Techniques for Fault Diagnosis of Electrical Equipment**

Table 1, illustrates various condition monitoring techniques which can be used for health monitoring of various important electrical equipment to ensure reliable operation. Stator/rotor winding faults and rotor body faults are most commonly accruing anomalies in generator and motors.
It is observed that for winding faults IRT can be used effectively, whereas due to accessibility constraints it is not suitable for rotor body faults and other internal faults in large machines, these can be effectively monitored by acoustic and vibration analysis. Cavitations in pumps and turbine, leaks in steam cycle and wall thinning of steam pipes are major problems in power plants. IRT and acoustic emission techniques are used for leaks and cavitations detection being a non-contact technique IRT can be preferred. Vibration analysis can also used to detect cavitations in pumps and turbines. In wind power plants structural defects of turbine blade and faults in gear train are very common. Ultrasound condition monitoring is very useful for monitoring structural health of turbines blades whereas vibro-acoustic and oil analysis are used for gear box fault detection. The advantage of lubricant analysis is the detection of fault at a very early stage.

Bearing is another vital component present in almost all rotating machines and due to its high rate of wear & tear, bearing condition monitoring is very important. Almost all CM techniques can be used for this purpose but vibration and acoustic techniques are used most commonly. Acoustic testing has an upper hand over vibration analysis as it can detect bearing wear out even when the speed of rotation is low. In transformers faults like loose connections, insulation inferiority and dampness in oil needs major attention. These can be detected by Infrared thermography whereas oil analysis is used to monitor both insulation deterioration and degradation of oil. Detection of corona, electric discharge, surge arrester, bushing and other HV equipment failure in substations are also some very important issues which are required to be dealt with for safe and reliable operation. IRT and air borne ultrasound being non-contact methods are the most suitable techniques which are used for this purpose. It is important to note that ultrasound condition monitoring system seems to be a less expensive solution as compared to other techniques and it can be used as a primary tool in organization with budget limitations.

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>TYPE OF INSPECTION</th>
<th>AUTOMATIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulator</td>
<td>Calculation of images' moment invariants as characteristic vector of recognition, classification by SVM algorithm [26]</td>
<td>Infrared trend evaluation package (IR-TEP), Invariant coefficient method[54]</td>
</tr>
<tr>
<td>Disconnector</td>
<td>Infrared trend evaluation package (IR-TEP), Invariant coefficient method[54]</td>
<td>---</td>
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<tr>
<td>Transformer</td>
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</tr>
<tr>
<td>Transmission line</td>
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<td>Model based on calculation of heat losses by convection and radiation[34]</td>
</tr>
<tr>
<td>Induction Motor</td>
<td>Model based on calculation of heat losses by convection and radiation[34]</td>
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</tr>
<tr>
<td>Leakage detection</td>
<td>---</td>
<td>Thermal model representing the temperature distribution[41]</td>
</tr>
<tr>
<td>Motor</td>
<td>Thermal model representing the temperature distribution[41]</td>
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</tr>
<tr>
<td>Motor, Bearings</td>
<td>Physical model of the element's temperature using a least square recursive method[40]</td>
<td>---</td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>---</td>
<td>Watershed segmentation, Neuro-fuzzy based classification [27]</td>
</tr>
<tr>
<td>Surge arrester</td>
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</tr>
</tbody>
</table>

Table 2: Infrared Thermography based Fault Diagnosis of Electrical Equipment

Unlike other condition monitoring techniques IRT is based on monitoring of temperature variation which is a common indicator in most of the electrical faults. Added with the advantages like non-contact testing, ruggedness, better noise immunity and possible fast and easy manual inspection, it is now extensively used in industries as a predictive maintenance tool. Table 2 presents both manual and latest automated analysis techniques proposed by different researchers for condition monitoring of electrical equipment using infrared thermography.
Conclusion
Condition monitoring has become a very important technology in the field of electrical equipment maintenance, and has attracted progressive attention worldwide. It brings numerous benefits for utility companies like reducing maintenance cost, lengthening equipment’s life, enhancing safety of operators, minimizing accident and the severity of destruction, as well as improving power quality. In this paper an attempt was made to summarize various techniques and methodologies used for condition monitoring of electrical machines. After a detailed study of each technology, it is concluded that the most suitable condition monitoring technique for a particular operation can only be decided by taking into consideration the factors like equipment under test, its loading, defect type and ambient conditions, etc. It was also observed that there is a great scope for research in the area of advancement in sensing, signal processing and artificial intelligence techniques, this is due to the fact that in near future, diagnostic and prognostic systems will likely focus more on online monitoring with automatic diagnostics and prognostics.

References


[31] AGAT laboratories Ltd., “oil analysis user guide”


