

Condition monitoring analysis methods for electrical machines: a review

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Abstract

This paper provides a review on condition monitoring analysis methods for electrical machines. An overview of condition monitoring is provided where online as well as offline monitoring is discussed. A section on vibration monitoring is included, since vibration monitoring is one of the most important online monitoring techniques. As part of vibration monitoring, background vibration, the effect of machine speed and load and variation of a signal at constant operating conditions are discussed. The paper further discussed time and process domain averaging, temperature effects, spurious low frequency ‘ski-slope’ effect and evaluation standards related to vibration monitoring. Various analysis methods exist for the condition monitoring of machines. These analysis methods are divided and discussed in this paper as deterministic and non-deterministic (or statistical analysis approach) methods. The paper ends with sections on condition monitoring measurements and noise filtering during condition monitoring.

Keywords: Condition Monitoring; Electrical Machines; Vibration Monitoring; Noise Filtering; Measurements.

1. Introduction

Condition monitoring and maintenance management are holistic and multidisciplinary in nature and are based on systems thinking. The concept of condition monitoring is to select a measurable parameter in the machine which will change as the health or condition of the machine deteriorates. Rao [1] provides an overview of condition monitoring and methodologies for fault detection. In condition monitoring, machines are regularly subjected to ‘health checks’ or vibration inspections. Advantages of condition monitoring include [2]: 1) lower levels of vibration which result in less mechanical wear, 2) less energy usage and 3) longer machine running time which result in less repair overheads.

Vibration monitoring is one of a number of online techniques which fall in the category of condition monitoring. In section 3 an overview of vibration monitoring is provided, followed by the effect of machine speed and load on the vibration level. The section ends with a discussion on the evaluation standards for vibration monitoring. Various international vibration monitoring standards are available [3]-[7].

There are three distinct forms of maintenance [8]: 1) breakdown maintenance, 2) periodic shutdown maintenance and 3) condition based maintenance. Breakdown maintenance is simply “run to failure” and allows no intervention in operation. The plant is maintained only when forced by a breakdown. Breakdown maintenance has low short-term capital expense, but high long-term capital expense. Periodic shutdown maintenance was once the industry norm. During periodic shutdown machines are overhauled and new components fitted irrespective of the operating condition. Condition based maintenance is the most cost effective form of plant maintenance. The plant is monitored or repaired only according to the diagnosed condition [8].

2. Condition monitoring

This section provides an overview on condition monitoring for both offline as well as online monitoring. Condition monitoring is divided into offline and online monitoring as shown in figure 1. In the case of offline monitoring the monitored object is not in a running state while monitored. Online monitoring is applied to running machinery. Condition monitoring is further divided into periodical and continuous. Periodical condition monitoring can be performed offline or online, but continuous monitoring is usually performed online.

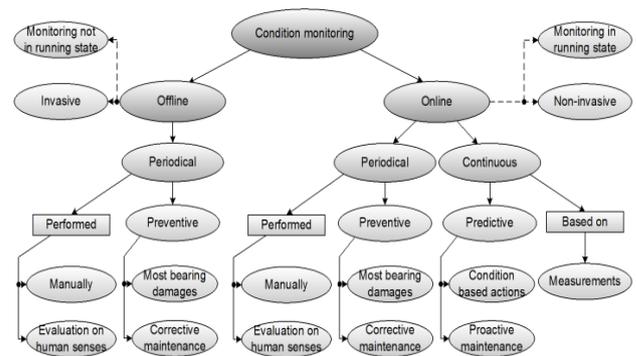


Fig. 1: Overview of Condition Monitoring.

Offline monitoring can be invasive, which means that the machine structure must be disassembled for monitoring. On the contrary, online monitoring is almost always non-invasive. Continuous online monitoring is based on measurements. Periodical monitoring is performed manually and can include evaluation based on human senses [9].

The advantages of continuous condition monitoring include [10]: 1) damages can be detected as soon as they appear, 2) trends can be formed automatically, 3) minimum need for labour, 4) detection of sudden changes is possible and 5) motors that are difficult to reach can easily be monitored. The advantages of periodical condition monitoring include [11]: 1) machines can be cleaned from dust or other particles when measurements are done, 2) investment for condition monitoring is smaller than in continuous condition monitoring schemes and 3) humans can discover changes in appearance such as mechanical damages, loose bolts, etc.

There are continuous online systems designed mainly for condition monitoring of electric machines. These systems usually consist of measuring and data processing devices, which can be permanently connected to a data bus supplying information to the analysing computer or data can be collected from the device occasionally. The decision on continuous data transfer or manually performed data collection is made mainly on the cost of instrumentation and labour [12].

Preventive maintenance with scheduled service procedures can prevent typical damages. For example, if the majority of bearings exceed their expected lifetime, the preventive maintenance can prevent most of the bearing damages by changing bearings before the expected lifetime expires [13]. On the other hand, if the expected lifetime cannot be determined (deterioration expectations are not known e.g. in the case of rotor faults) the scheduled maintenance is relatively inefficient [8].

Maintenance can be corrective which means that broken components are replaced or repaired. Unplanned downtime and possible breakdown of machinery can make corrective maintenance very expensive [9]. Predictive maintenance means condition based actions. These require condition monitoring in order to detect deterioration. Proactive maintenance aims to improve the object (process) so that the probability of the damage is decreased in the future [14].

3. Vibration monitoring

This section provides an overview of vibration monitoring. Vibration monitoring is one of a number of online techniques, complementary to such measures as performance checking using non-dimensional flow, measurement of pressure, temperature, axial movement, etc. All of these techniques, collectively called condition monitoring, have the common objective of showing malfunction or deterioration in machine operation in a numerative manner. They can be used to assess the need, if any, for corrective action [11].

Vibrations on machines are in general periodic in nature, although some unsteadiness in the signal is to be expected. This means that the signal repeats itself after a definite time interval (usually the time taken for one revolution). Periodic vibration may be considered as the oscillation of a particle about a fixed datum position [13]. The smallest form is where the displacement varies sinusoidally with time. More complex vibrations may be considered as being the addition of many different sine waves (usually in the form of one or more harmonic series).

The acceleration component in a vibration signal depends on the square of the frequency, which means that if significant high frequency content is present in a signal, the acceleration level will be high and conversely, if the high frequency content is of interest, the acceleration should be measured [15].

Mechanical and magnetic forces cause vibrations in electric machines. The principal source of vibration in electrical machines are: 1) the attractive magnetic force between the rotor and stator [16], 2) the slot harmonics [11], 3) the saturation harmonics, 4) the response of the stator end windings to the electromagnetic forces on the conductors [17], 5) the rotor eccentricity and the flexibility of the rotor [18].

In addition, mechanical load can have eccentricity or it can induce vibration due to its mechanical structure or the load can process materials that give shocks to the motor axle or to the stator frame

(crushers, pumps, etc.) The vibration components caused by normal operation should be considered and separated from the machine fault induced vibration [16].

Overall vibration level monitoring is quite commonly used [17]. The overall limits for vibration are given by the international standard ISO 10816-1 [6], which define the RMS velocity limits for the good, allowable, just tolerable and not permissible classes. Overall level monitoring offers quite limited means for condition monitoring, because it cannot reveal incipient faults. On the other hand, many non-cyclic bearing faults increase the overall vibration level and the vibration is spread over a wide frequency range so that frequency analysis alone cannot reveal the fault [18].

3.1. Background vibrations

Background vibration or vibration originating outside the machine is the first possible cause of non-repeatability. Some machine bedplates, for example pumps mounted on a thin cover sheet, are notoriously responsive for the running condition of nearby machines. Vibration can easily be transmitted through interconnecting pipework, which respond to pulsating forces [19].

On some machines the vibration level is quite high even with the machine shut-down. One way to overcome this problem of variable measurement is to ensure that the vibration levels are obtained with the machine both offline and online. Another method is to provide isolation between the two machines in the form of anti-vibration mounts [20].

For meaningful trend results the background vibration should be small compared to that experienced when running. A beat occasionally occurs in the vibration level due to interaction between machines running at slightly different speeds [15].

3.2. Effect of machine speed and load

The measurement of consistent results on variable speed and load machines are very difficult. The machine should be brought back to the same condition, before the measurements are taken, otherwise the effect of changes in speed and load on the measurements must be taken into account.

Speed can affect overall level results, when running in the proximity of the resonant or critical speed of the machine or its support. On high speed turbines, even changing the temperature of the lubricating oil can have a dramatic effect, especially when the machine is prone to instability originating in the bearings [15]. Similarly some machines are prone to changes in load. For example process pumps running well away from their maximum efficiency point, can generate a significant frequency component at Vane passage frequency, which can vary from reading to reading [3].

3.3. Variation of signal at constant operating conditions

Most signals in the real world consist of a combination of two types of signals, namely a 'deterministic' portion, which is usually the signal of interest and a 'random' portion, which is generally considered as noise. Time domain averaging and process domain averaging can be used to enhance the two different parts of the signal [3].

3.3.1. Time domain averaging

Time domain averaging means the data is averaged as it is acquired by the instrument, before processing commences. It should only be used when the signal is repetitive and a consistent trigger point is available. The signal-to-noise ratio (SNR) can be improved. Time averaging is particularly useful in the analysis of signals from faulty gearboxes. It cannot be used with success on rolling bearings, since there is not a purely rolling action and there is a small amount of slip of the roller on the track [21].

3.3.2. Process domain averaging

A statistically more accurate estimate of the signal can be obtained through process domain averaging. The SNR will not be improved. Each time a process is executed, the individual values of the output can vary to some degree. For example, the values in each line of a spectral output can show some variation in amplitude although tending towards a mean value. Averaging will provide a better estimate of this mean value.

The time taken to acquire one memory period in spectrum analysis depends on the number of lines chosen for the spectrum (i.e. resolution), and the frequency range taken [22].

The number of averages (or memory periods), which should be taken depends on the variability of the data, and obviously affects the time taken to complete the measurements. In practice, it is found that on most machines a number of averages, corresponding to a 30 second measuring period, are adequate to provide consistent data [15].

3.3.3. Temperature effects

A high impedance accelerometer can be used up to a temperature of 250 °C. A normally used low-impedance accelerometer with built-in electronics is not recommended for use as a roving pick-up on hot surfaces (more than 100 °C) [15].

It is recommended that an accelerometer with a good thermal stability is used if machines with hot surfaces are to be measured. Normally accelerometers which use the piezo-electric crystal in a shear configuration have better thermal stability than those using the crystal in compression. The bearings of an AMB system are designed to withstand certain temperatures. High temperature sensors are recommended for AMB systems operating under high temperature conditions [23].

3.3.4. Spurious low frequency ‘Ski-slope’ effect

A problem which is quite often encountered in taking measurements is the generation of low frequency noise. It is particularly noticeable, when the acceleration signal is integrated and with low frequency ranges (e.g. 0 – 200 Hz). For a decrease in frequency by a factor of 10, the noise floor will increase by 10 for acceleration, but by 100 for velocity. Typical noise are the following: 1) base strain effects (affected by ambient conditions and thermal transients), 2) power supply effects (i.e. transient caused by switching on the power supply) and 3) cable noise [24].

3.3.5. Evaluation standard for vibration monitoring

The machine condition can be determined by using the effective value of the vibration velocity. This value can be determined by almost all conventional vibration measurement devices. The international standard for mechanical vibration on non-rotating machines (ISO 10816-3) separates machines into the following groups that take the type of installation into account [7]: A) the vibration values from machines are put into operation, B) machines can run in continuous operation without any restrictions, C) vibration values indicate that for a limited period of time the machine condition is not suitable for continuous operation and corrective measures should be taken at the next opportunity and D) dangerous vibration values and damage could occur to the machine [5], [6].

4. Condition monitoring analysis methods

This section provides an overview on condition monitoring analysis methods. Various analysis methods exist for the condition monitoring of machines. These methods can be divided into deterministic and non-deterministic methods [25]. Deterministic means that the physical parameters of the object determine the condition estimate with the aid of heuristics and calculations directly. Deterministic methods include parameter estimation, rule-based

methods, fuzzy-logic and mathematical modelling. A diagram showing the different condition monitoring analysis methods is provided in figure 2.

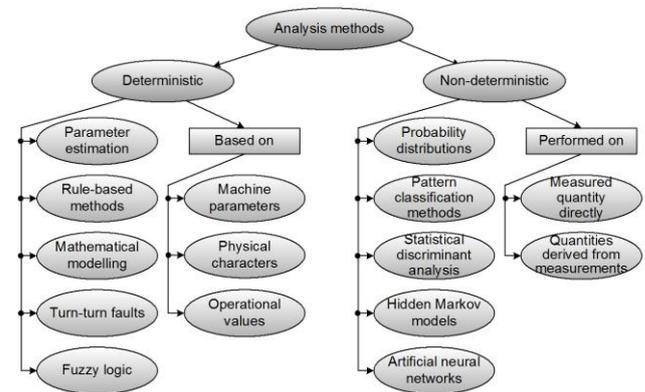


Fig. 2: Condition Monitoring Analysis Methods.

Non-deterministic means that a significant degree of contingency or unknown determining factors exist. The measured quantity does therefore not determine the condition directly. Non-deterministic methods include probability distributions and artificial neural networks. Non-deterministic methods often use statistical pattern classification for decision-making [26].

Condition analysis procedure often includes both types of analyses. Often, based on some deterministic model, the values describing the condition are formed. These values are then post processed with non-deterministic methods (e.g. in the article of Kyusung [27]).

4.1. Deterministic approach

A deterministic approach (shown in figure 2) based on known machine parameters, parameter estimation, physical characters and operational values is suitable for indication of faults that have a definite limit to distinguish faulty and healthy conditions. This is possible especially in cases, where the measurement is closely connected to a physical phenomenon or an indication is based on estimated values and a mathematical model [28].

A purely deterministic approach becomes difficult if indication of incipient faults has to be automated. A visual inspection of spectrum components can reveal a fault that cannot be given by deterministic limits or equations [29].

Turn-to-turn faults are an example of faults that can be indicated by a purely deterministic approach. Symmetrical components of current can be calculated when at least two phase currents are measured (and no earth fault is present). A negative sequence current can indicate turn-to-turn faults or asymmetric supply [30]. It is necessary to recognise the characteristic negative sequence impedance offline to avoid a false positive fault indication. In the article by Kliman [31], this is done with the calculation of the characteristic negative sequence impedance in a healthy condition. Fuzzy logic has been used in the condition monitoring analyses by Mechefske [32] and Benbouzid [33]. Mechefske used fuzzy logic in order to classify frequency spectra derived from a vibration signal from a low speed bearing. Fuzzy memberships were formed using the average and standard deviation of each useful frequency component from healthy and different faulty case measurements.

4.2. Statistical analysis approach

Statistical methods (shown in figure 2) are often used in order to indicate faults. Statistical analysis is performed on the measured quantity directly or to the quantity derived from measures. The use of statistical analysis using an artificial neural network (ANN) has been demonstrated (e.g. in the article of Chow [34]) in which a neural network indication of a bearing fault is presented. Schoen [35] has used ANN and the stator current measurement in order to indicate rotor eccentricity.

Paya and Esat [36] have used ANNs in fault diagnostics using Wavelets in order to pre-process the vibration signal. The main difficulties of ANNs are that educational data are case specific and other factors than faults can cause conditions that indicate faults.

A comparison between the deterministic autoregressive modelling technique and the ANN technique is made in research of Baillie [37]. Other statistical methods that are used in condition monitoring include clustering of data [38], statistical discriminant analysis and Hidden Markov models [39].

A time-frequency analysis can be used when the changes in measured quantities are small and time variant. This is a normal situation in the case of very incipient faults or when the measured quantity is weakly linked to faults. Time-frequency transformation is most often performed by the short time Fourier transform (STFT) or by Wavelet transform (WT). The indication of faults in time-frequency analysis can be automated by using, multi-layer perceptron (MLP) neural network or statistical pattern recognition methods such as discriminant analysis or self-organising maps (SOM) [20], [40].

5. Condition monitoring measurements

This section provides an overview on condition monitoring measurements. If the condition monitoring of an electric machine is based on measurements there are two ways to indicate an alarm level for deterioration. The first one is the use of alarm limits on a measured or analysed quantity and the other is the change in the long-term trend of measurements, which indicates change in the motor or drive. Measurements can be analysed in time- or frequency domain or in combination of these (time-frequency analysis) [41].

The following are some of the quantities that indicate the condition of an electrical motor: 1) stator current, 2) power, 3) axial, stray and air gap flux, 4) electrical and mechanical torque, 5) vibration, 6) temperature and 7) rotational velocity. Some of the techniques that indicate the condition of an electrical motor are: 1) electrical and magnetic techniques, 2) measurement of the rotor displacement, 4) temperature images, 5) chemical analysis and 6) visual inspection [2].

Online condition monitoring can utilise all of the listed techniques. However, some of these techniques require expensive devices and are therefore used mostly for the monitoring of big generators (partial discharge, gas analysis, etc.). In addition, some methods require installation that can be made only when the motor is disassembled. For example, an air gap flux measurement requires a sensor in the air gap, but the axial flux can be measured outside the motor frame [12].

6. Noise Filtering during condition monitoring

This section provides an overview on noise filtering during condition monitoring. When analysing the complicated vibration produced by several machines, the measurement of periodic components embedded in noise becomes a problem. If the frequencies and amplitudes of any periodic components in the vibration can be measured, then this is the first step towards tracing their origins [34].

A problem that may arise is that associated with the round-off error through calculation. In situations where the detection of weak components is required, it may be more appropriate to separate and classify all possible sought waveforms, before performing any kind of filtering or smoothing operation on the signal [42].

If this is not carried out beforehand, the weak components of the signal that need to be identified may be eliminated, particularly when applying an average to a signal with very weak components, embedded in high-level noise. This would be likely to occur, because the quantization and round-off errors, through the averaging process, may eliminate the little difference there is between those signals which have weak components and those which do not [42].

A basic technique used for noise filtering is based on a time-averaging procedure. It is important to point out that with this technique, if the correct phase synchronisation is not carried out, the specific component that is being sought will be eliminated. Furthermore, when one attempts to analyse the whole spectrum signature, it is necessary to perform a phase synchronisation for each component present in the signal, and this may be rather impractical [43].

According to Bendat and Piersol [43], this procedure is also problematic when applied to signals which have non-stationary components present, as they can generate severely distorted results. This is the case of the petroleum wellhead vibration (described by Bendat and Piersol), which includes components caused by fluid slug vibration. In these situations, Bendat and Piersol argue that there may be a strong temptation in analysing non-stationary data to treat it as if the data were a sample record from a stationary random process.

7. Conclusion

This paper provided a review on condition monitoring and discussed the effect of machine speed and load on the vibration level. The low frequency 'ski-slope' effect was also discussed.

Condition monitoring is divided into offline and online monitoring. Periodical condition monitoring can be performed offline or online, but continuous monitoring is performed online. Predictive maintenance detects deterioration and proactive maintenance aims to improve the object (process) so that the probability of the damage is decreased in the future.

Vibration monitoring is one of a number of online condition monitoring techniques. Various international standards for the mechanical vibration of non-rotating and rotating machines exist, which can be used to categorise the vibration level of a machine. Condition monitoring analysis methods can be broadly divided into deterministic and non-deterministic methods.

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