SIGNATURE ANALYSIS METHODS TO DETECT FAILURES IN ELECTRIC MOTORS

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ABSTRACT. The monitoring and diagnosis of electric motors are a serious challenge for engineers and researchers in the industry where minimising maintenance costs and adherence to production lead times are of utmost importance. Numerous methods exist to solve these tasks, such as monitoring of the mechanical vibrations, thermal inspection, acoustic monitoring, etc. They are based on the fact that for a healthy machine, the shape of the observed signal has some typical profile, also referred to as a signature. The changes in load and the various types of damages lead to the occurrence of additional and atypical harmonics in the spectrum of the signal that have a noticeable impact on the profile of that signal. The choice of a suitable signature analysis method allows for early detection of failures, such as the emergence of a short circuit, a winding disruption, eccentricity or vibrations due to damages of a bearing or to an atypical load. In this way it is possible to perform a planned repair instead of an emergency one, which can be of a considerable economic effect. This paper provides an overview of some basic methods for signature analysis. A particularly promising amongst them is the Motor Current Signature Analysis (MCSA), which is a sensorless and a non-invasive method, and at the same time it allows for remote site-based investigation.

Keywords: motor faults, signature analysis, vibration analysis, health monitoring, Motor Current Signature Analysis (MCSA)

МЕТОДИ ЗА СИГНАТУРЕН АНАЛИЗ ЗА ОТКРИВАНЕ НА ПОВРЕДИ В ЕЛЕКТРИЧЕСКИТЕ МОТОРИ

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РЕЗЮМЕ. Контролът и диагностиката на електродвигателите са сериозно предизвикателство за инженерите и изследователите в индустрията, където минимизирането на разходите за поддръжка и спазването на сроковете при производство са от ключово значение. Съществуват множество методи за решаване на тези задачи, такива като следене на механичните вибрации, термично обследване, акустичен мониторинг и др. Те се основават на факта, че за една здрава машина формата на наблюдавания сигнал притежава характерен профил, наричан още сигнатура. Промяната на натоварването и различните видове повреди водят до възникване на допълнителни и нетипични хармоници в спектралния състав, които оказват осезаемо влияние върху профила на този сигнал. Изборът на подходящ метод за сигнатурен анализ позволява ранно откриване на повреди от типа на: възникване на късо съединение, прекъсване на намотка, възникване на ексцентрицитет или вибрации вследствие на повреден лагер или нетипично натоварване. По такъв начин е възможно реализирането на планов вместо авариен ремонт, което може да има съществено икономическо значение. В настоящата статия е направен общ преглед на някои основни методи за сигнатурен анализ. Като особено перспективен сред тях се очертава анализът на формата на тока (Motor current signature analysis-MCSA), който се явява безсензорен и неинвазивен метод, а освен това дава възможност за отдалечено от обекта изследване.

Ключови думи: повреди в електрическите мотори, сигнатурен анализ, вибрационен анализ, анализ на профила на тока

Introduction

In a global aspect, electric drives are amongst the main consumers of electricity as they are involved in all areas of modern life - industry, medicine, and everyday life. According to various sources, electric drives nowadays consume between 50% and 70% of all of the produced electricity. This reserves them a very special place in automation control systems in both manufacturing plants and household appliances. That is why the requirements imposed on their effective use are constantly growing which means deployment of faster and more complex control algorithms. At the same time, the high speed of continuous production requires very high reliability. Unfortunately, even the most sophisticated technologies cannot avoid the possibility of failures. On the one hand, motor faults can emerge due to mechanical problems and on the other hand, they can be electrical in nature. The earlier the failures are encountered the less are the material and financial losses. Every retardment in obtaining the information of possible faults may affect the whole motor operation, or deteriorate, or even stop the entire manufacturing process. Consequently, large revenue losses and maintenance costs may occur.

Contemporary achievements in physics and material science lead to the invention and production of fast and accurate sensors such as resistive and semiconductor-based strain gauges, piezo transducers, accelerometers, Hall sensors, Rogowski coils, etc. The dramatic development of microelectronics and the increasing computational capability make it possible not only to perform fast data logging but also to implement complex mathematical algorithms into digital hardware that is able to make calculations in real time.

In this paper, some common faults in electrical motors are briefly introduced. Prospective methods adopted for analysis of motor faults are also discussed such as signature analysis techniques. Some common instrumentation apparatus is also mentioned in the paper.

Faults in electric motors

Faults in electric motors are mainly classified as electric or mechanical. Common failure types include bearing problems (including gearbox), rotor or stator windings, breakage of rotor bar, brushes or slip ring, static or dynamic air-gap irregularities, rotor imbalance, etc. According to a survey held by the Institute of Electrical and Electronics Engineers (IEEE) and the Electric Power Research Institute (EPRI) (IEEE Std. 493-1997; Allbrecht et al., 1986) the percentage of fault occurrence is distributed as shown in Table 1. It can be seen that the bearing faults (mechanical) are prevalent in frequency of emergence followed by stator faults.

Table 1.

Study	Bearing faults [%]	Stator faults [%]	Rotor faults [%]	Others [%]
IEEE	42	28	8	22
EPRI	41	36	9	14

According to (Karmakar et al., 2016), major faults in induction motors can be categorised as:

- mechanical faults – broken rotor bars, load imbalance, air gap eccentricity, bearing damage, rotor and stator windings failure;
- electrical faults – imbalance of the supply voltage/current, single phasing, under/over voltage, reverse phase sequence, earth fault, overload, inter-turn short-circuit fault, crawling;
- faults related to the environment – ambient temperature, external moisture, vibrations due to working in harsh environments.

A non-exhaustive summary of these typical failures is given in Fig. 1 (Siddiqui et al., 2014). A thorough discussion on the causes of AC motor failure analysis that completes the overall picture can be found in (Bonnett, 2000).

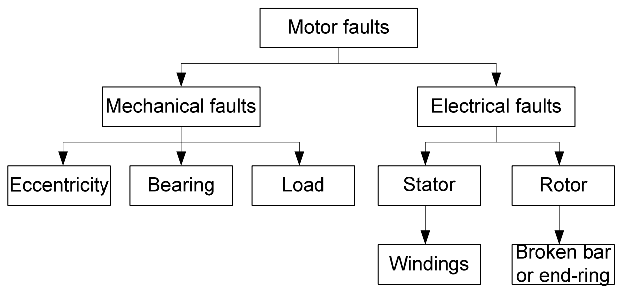

Fig. 1. General classification of motor faults (Siddiqui et al., 2014)

More than 66% of the failures are detected during operation and about 28% are detected during maintenance procedures (IEEE Report, 1985). Rotor faults can be observed either through monitoring the rotor currents, if there are any windings on the rotor at all, or more frequently, by monitoring stator currents. Having said all of the above, the importance of the predictive analysis and the need of preferably non-invasive measurement tools are obvious.

Digital signal processing

Both vibration and current monitoring techniques require conversion of the measured quantity into voltage and subsequent fast data acquisition. This process imposes signal conditioning and filtering in order to limit the spectrum of the signal, subsequent transformation and scaling/normalization, data reduction, and sampling. With properly selected digital filter bandwidths and adequate sampling rates, sigma-delta ADCs allow for supply frequency rejection, which means that no additional signal is introduced during processing. Nowadays, converters available on the market have high dynamic range (up to 24-bit) and high sampling rate in the order of a few hundred MHz. Their capabilities often exceed the performance requirements and provide effective current signature analysis.

The steps involved in digital signal processing are depicted in Fig. 2:

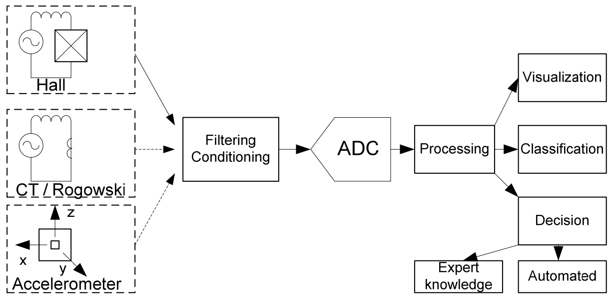

Fig. 2. Digital signal processing and data analysis

As it is shown in the figure the steps of data analysis can also be done digitally concluded with automated visualization, failure classification and decision making. Each of these steps represents a highly sophisticated algorithm although the decision making often requires an expert knowledge.

Primary sensors

The information about the health condition of a machine is obtained by measuring a wide range of signals. These signals include vibration, current or voltage (stator and/or rotor), magnetic flux, torque, acoustic noise, temperature, etc. Some of these quantities can be easily obtained while others are virtually impossible to be read or require constructive modifications, or are simply too expensive. That is why the main sensing components used in motor failure analysis include resistive temperature devices (RTD), accelerometers, Hall sensors, Rogowski coils, and current transformers. The two latter are most widely used for signature analysis (mechanical – vibrations or current related - MCSA).

Analysis methods

Health condition monitoring and analysis methods can be derived in the following general categories (Mehala, 2012, with additions):

1. Thermal model based on:
   - Finite Element Analysis (FEA)
   - Thermal network analysis
2. Root Mean Squared (RMS)
3. Frequency domain
   - Fast Fourier Transform (FFT)
4. Time-Frequency techniques
   - Short Time Fourier Transform (STFT)
   - Gabor Transform (GT)
   - Cohen class distribution
     - Wigner –Ville distribution (WVD)
     - Choi-Williams distribution
     - Cone shaped distribution
   - Wavelet Transform (WT)
5. Time series methods
   - Spectral estimation through ARMA models
   - Welch method
   - MUSIC method
   - Periodogram
6. Cepstrum analysis
7. Park vector approach

The first two categories are discussed in (Siddiqui et al., 2014). The FEA method is based on differential equations and thus it is compute intensive and time consuming, but very precise. The thermal network (Lumped parameter based model) is much simpler, but less accurate than the FEA and can be slow. The RMS method represents a simple statistical calculation but it is much less informative and is mainly used for a rough indication of the motor loading.

The frequency domain analysis uses the Fast Fourier Transform (FFT) and it is the most common signal processing method used for online condition monitoring. This is due to the fact that many mechanical and electrical failures generate signals whose frequencies can be determined by knowledge of motor parameters. These fault signals appear in various sensing signals, including vibration, current, and flux. The FFT analysis is based on the fact that each periodic signal can be decomposed into a sum of sinusoids, thus converting the signal from the time domain into the frequency domain. The vice versa conversion is also possible. In their work, (Marcelo et al., 2012) use FFT to detect real-time asynchronous motor damage – broken rotor rod, bearing failure, eccentricity and short circuit.

The time-frequency techniques include several algorithms amongst which the STFT and WT are the most common. The STFT method provides strong capabilities to diagnose faults in the transient conditions. It has good time resolution but has poor frequency resolution. In contrast with the FFT, the wavelet transform decomposes the signal into a set of non-sinusoidal waves. It is usually applied to impulse waveforms that are not convenient to be represented as a sum of sinusoidal components. This transform is being initially used for seismic analysis. It provides capabilities to extract local parameters of the signal with very good precision. (Siddiqui et al., 2012) use the WT method for broken rotor bar fault detection in induction motors.

The cepstrum analysis is a result of taking the inverse Fourier transform (IFT) of the logarithm of the estimated spectrum of a signal. The word "cepstrum" is derived by exchanging the two halves of the word "spectrum". (Bogert et al., 1963) describe it as “the power spectrum of the logarithm of the power spectrum”. As with the WT, the original application of this method is the detection of echoes in seismic signals. Operations on cepstra are labelled quefrency analysis, liftering, or cepstral analysis.

The Park vector method is a relatively new technique, which is applied in the diagnosis of rotor faults, inter turn stator faults, and unbalanced supply voltage (Ourici et al., 2012). An undamaged machine theoretically shows a perfect circle when plotting the two axes, namely the active stator current and the reactive stator current (d, q), obtained from the Park transform. An unbalance due to turn faults may result in a more elliptic representation of the plot giving a clear indication of a motor fault.

After the analysis stage of the digital signal processing, a decision making algorithms take place. The most common ones include the category of statistical classification algorithms which solve the problem of identifying to which of a set of categories some new set belongs, and the category of intelligent methods like artificial neural networks (ANN) (Ourici et al., 2012) and fuzzy logic (Benbouzid et al., 2001; Siddique et al., 2003). These methods will not be discussed in this paper as the topic is too broad.

Instrumentation apparatus

Numerous tools exist regarding the signature analysis both in terms of the vibration and of the MCSA measurements. Some commercial tools exist for vibration measurement, such as the portable Fluke 810 Vibration Tester (worth 9000 EUR), Fluke 805 Vibration Meter (2000 EUR), MIDE Shock & Vibration Accelerometer Loggers (about 850 – 1700 EUR), and for current signature, power quality and motor analysis, such as IRIS Power MDSP3 that detects rotor cage winding faults including broken rotor bars, cracked shorting rings and unequal air gaps (5000 EUR), Fluke 438-II (8500 EUR) or SEMAPI Test-I-Go (12000 EUR). All mentioned tools are very high-quality, powerful, portable, and versatile solutions but for some users and cases they are quite pricey. On the other hand, very low-cost and even open-source solutions exist, such as the Arduino microcontroller platform equipped with the corresponding accelerometer, Hall effect or current probes whose price can be as low as 50 EUR, or the TI MSP432 ARM MCU that is powerful enough to do calculations in real time. The high-end of low-cost solutions includes single board computers (SBC), such as the Raspberry Pi and TI Beagle Bone. Beside the proprietary software solutions, the common software used for offline analysis or plotting the results and taking a decision is based on mathematical packages, such as Matlab, Scilab or Octave, and some popular programming languages as Python and its libraries Numpy, Scipy and Matplotlib.

Since the data processing path can be too long and thus significantly slow, nowadays, programmable logic devices become more and more common, such as the Field Programmable Gate Arrays (FPGAs). Because these integrated circuits don't have hard logic architecture (ALU, registers, etc.) but only logic gates and memory, they are capable of implementing parallel running algorithms. It makes it possible to embed the signal conditioning, analog to digital conversion, signal decomposition (FFT or WT), and an artificial neural network onto a single device. This way, a true real time data processing and decision making can be done.

Conclusions

A number of diagnostic methods exist for identifying different failure modes of electric motors, such as mechanical vibration control, thermal imaging, acoustic monitoring, etc., but most of these methods require expensive sensors or interference in the design of electric motors. It is well known that the various types of damage affect the shape of the current. This allows it to be analysed in a sensorless and non-invasive way which is mainly done by performing Motor current signature analysis (MCSA) or Wavelet Transform (WT) technique. The analysis of the current profile is done by observing its harmonic spectrum and searching for typical frequencies (artifacts), as is the case with the mechanical vibration analysis. If there is a fault, harmonics emerge that are not typical for the healthy machine. This method allows early detection of failures such as increased risk of short circuit, winding disconnection, eccentricity or vibrations due to damaged bearing or load abnormalities. The discussed techniques make it possible to transform the maintenance process from reactive to preventive to predictive one. In this way, it is possible to implement a planned instead of an emergency repair, which is of utmost importance in the production. This makes the topics discussed in the research paper relevant, practical, and with a good potential economic impact.

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