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MULTICRITERIA DIAGNOSIS OF SYNCHRONOUS MACHINE USING THE WELCH METHOD

WIELOKRYTERIALNA DIAGNOSTYKA MASZYNY SYNCHRONICZNEJ Z UŻYCIEM METODY WELCHA

A b s t r a c t

This paper discusses the detection of internal faults in the stator and rotor windings of synchronous machines. Using current signature analysis, it is demonstrated how by using low cost equipment, it is possible to detect the fault by monitoring the currents. The process of detection is totally optimized, and the processing time is enough to identify the fault before the total machine damage. Using the spectrum of the healthy machine as a reference, the followed methodology allows the timely and reliable detection of faults.

Keywords: *synchronous machine*, *spectral analysis*, *fault diagnosis*

S t r e s z c z e n i e

W niniejszym artykule opisano metodę wykrywania wewnętrznych uszkodzeń w uzwojeniach stojana i wirnika maszyny synchronicznej. Przedstawiono sposób zastosowania analizy widmowej monitorowanych prądów do wydzielenia sygnałów o uszkodzeniu. Proces wykrywania jest zoptymalizowany i umożliwia wykrycie uszkodzenia maszyny przed jej zniszczeniem. Wzorcem odniesienia jest widmo prądów maszyny nieuszkodzonej. Zastosowana metodologia zapewnia terminowe i niezawodne wykrywanie błędów.

Słowa kluczowe: *maszyna synchroniczna*, *analiza widmowa*, *diagnostyka uszkodzeń*

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1. Introduction

The need to reduce production costs, maximize the return on investment and decrease CO_2 emissions is leading to new ways of operating existing processes and develop new and more integrated industrial processes. These more integrated systems demand continuous information from the assessment of their components. To collect, transmit and process all available data is not a trivial task and must be timely and reliably executed [1].

Addressing technology gaps at the interfaces between the processes, mechanical and electrical domains, and realizing energy savings from integrated operations are factors that motivate and extend research on the multicriteria diagnosis of synchronous machines. In addition, a unique rotor-mounted sensing system was specially designed to collect data from different sensors installed over the rotor [2]. It is strongly believed that this method for acquiring data would allow the reliable detection of faults, even more so when used in combination with an automated monitoring algorithm or process [3].

Synchronous machines (SM) are used mostly in high power operations and as an alternating power source. In general, SM can be found where constant speed operation, power factor control and/or high operating efficiency are required. Moreover, it's high torque characteristics at low speed, and in applications where a wide speed adjusting range is necessary, SM have proven their ability to improve stability in variable-frequency drive applications.

Energy-efficient drive technologies should be well dimensioned, and the control strategy designed according to load conditions. Reducing the input power of the system is a direct way of reducing the cost of production and thus to increase the efficiency of the systems. However, this does not guarantee the availability of the system to meet the requirements of the load. Therefore, it is necessary have systems capable of fault detection and ideally, prediction [4].

Condition monitoring systems are becoming more accurate, and less expensive. Their applications in complex systems allow the assessment of the integrity of the system required for long term scheduling [5]. Loading and maintenance strategies are the two main tasks that directly link the information provided. Trying to minimize the number of unexpected shutdowns, understanding the behaviour and/or the early detection of faults are desirable for every system. Therefore, it seems clear and reasonable to develop algorithms that inform about the assessment of the system allowing a better operation and thus, an improvement in efficiency [6].

2. Motor current signature analysis. Stator and rotor inter-turn fault detection

Initially used to study anomalies and faulty condition in induction motors, the so-called motor current signature analysis (MCSA) has been proven to be a tool for detecting faults such as broken rotor bars, air gap eccentricity, shorted winding, etc [7, 8]. MCSA can identify these problems at an early stage and thus avoid collateral damages or complete failure of the motor.

Detecting stator and rotor winding short-circuits has been analyzed for several years already. In 1996, a novel method of detecting short circuits in both the stator and rotor windings of synchronous generators has been proposed by detecting changes of the harmonic content in the rotor and the stator current spectrum. More recently, new diagnostic tools to determine when significant insulating aging has occurred have been introduced such as polarization-depolarization current, dielectric spectroscopy and on-line leakage current monitoring [6].

Regarding documentation associated with stator and/or rotor short-circuit faults, most of the available literature relates to the monitoring of failures in synchronous generators [9, 10] or in permanent magnet SM [11]. In [12], the effects of stator interturn short-circuit are analyzed using the field current. The same author as [13] added a rotor search coil voltage signature analysis to identify winding the short-circuit in synchronous motors.

The authors in [14] have developed a mathematical model to study the winding failure of a salient pole synchronous machine calculating the spectra of the stator and field current.

3. Experimental platform configuration

A salient pole synchronous machine (SPSM) ready for non-invasive fault diagnosis tests under different severity levels is available. Running as a generator or as a motor, it is possible to set-up either mechanical or electrical faults or to combine both.

Operated as a motor only; stator and rotor interturn short circuit faults are discussed in this paper. The features of this synchronous machine are described in Table 1.

Table 1

SPSM parameters

Power [kW]	7.5
Voltage [V]	400
Current [A]	15.8
Rotational speed [rpm]	1500
Power factor	0.8
Frequency [Hz]	50
Number stator-slots	42
Field current [A]	8.56
Field voltage [V]	50
Efficiency [%]	85.2
Mass [Kg]	263
Protection level	IP23
Cooling	IS01
Assembly	IM100

The stator of the machine consists of 42 slots with double layer windings. The configuration of the winding can be modified, all the ends of every group of windings are accessible allowing the simulation of many fault conditions to be performed.

All experiments were carried out under the same machine configuration, and special attention was given to guarantee the repeatability of the experiments. The data-set was collected at a sampling frequency of 25 kS/s during two seconds using the Matlab data acquisition toolbox.

A National Instrument NI-USB 6255 acquisition card it is available. The most relevant features are as follows:

– 80 analog inputs (16-bit),
– 125 MS/s single-channel (750 kS/s aggregate).

3.1. Stator short-circuit fault

In Figure 1, a stator winding configuration is presented. Each phase consists of two parallel branches of one group of three coils and another of four coils connected in series. In [15], the utility of the circulating current was used for fault detection in SM.

Simulations of different levels of stator interturn short-circuit were made by placing a variable resistor connected in parallel with the phase ‘c’ (second parallel branch) in a group of four coils.

Different levels of short-circuit were obtained controlling the deviated current from 0 to 2 amperes, at increments of 0.25 amperes with the motor running at 60% of rated power.

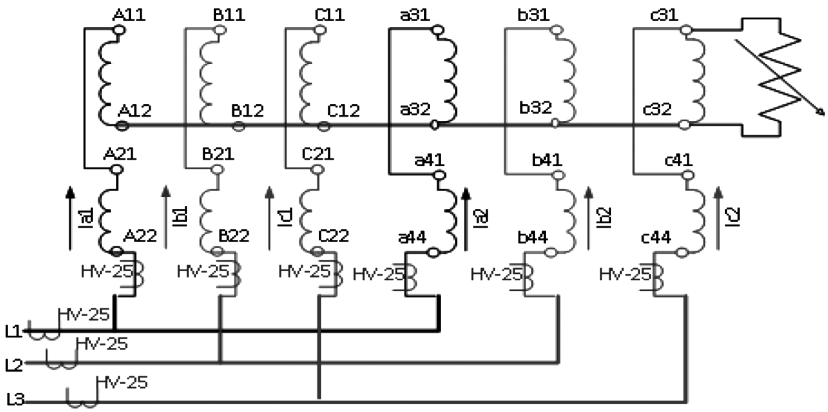

Fig. 1. Stator winding configuration

3.2. Rotor short-circuit fault

The rotor is a salient 2p poles rotor with configurable field winding. In this case, Fig. 2, it is possible to short circuit 90% or 10% of the coils that creates the pole. The experiments were carried out for different set points varying the load of the machine from 0% to 100% of rated power, with the pole four having 90% of shortened coils.

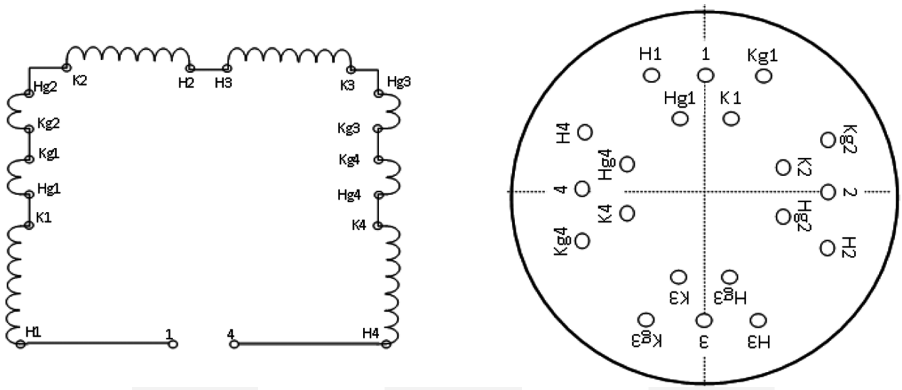

Fig. 2. Rotor winding configuration

4. Preprocessing and statistical analysis of current spectrum

In order to comply with the mathematical requirements, our data was truncated from the first negative to positive zero crossing, and to the last positive to negative zero crossing. Additionally, each signal was centered to have a mean of zero and scaled to have a standard deviation of one using the standardized z-scores MATLAB algorithm. The condition of the second-order stationary was also verified.

Once all mathematical requirements are fulfilled, the next step was classifying them according the level of fault and for each load level. At this point, the data set is ready to be processed.

4.1. Mathematical formulation

We are interested in finding those frequency components that may change when the synchronous motor is running under fault condition. Therefore, all datasets were obtained during only steady-state conditions. The collected signals under this condition, are considered as random signals from a sequence of time samples or just called discrete-time sequence.

$$\{y(t); t = 0, \pm 1, \pm 2 \ldots\} \tag{1}$$

It is assumed to be a sequence of random variables with a zero mean given by the expectation operator $\{E; E\{y(t)\} = 0\}$ for all t. The time index t is expressed in units of the sampling interval, that is,

$$y(t) = y_c(t \cdot T_s) \tag{2}$$

where:

$y_c(\cdot)$ – is a continuous signal,

T_s – sampling time interval.

and has finite energy;

$$\sum_{t=-\infty}^{\infty} \left| y(t) \right|^2 < \infty \tag{3}$$

Then, the sequence $\{y(t)\}$ possesses a discrete-time Fourier transform (DTDT) defined as:

$$Y(\omega) = \sum_{t=-\infty}^{\infty} y(t) e^{-i\omega t} \quad \text{(DTFT)} \tag{4}$$

Only frequencies below 5 kHz are considered. Hence, effects which might be incurred by the sampling process, such as aliasing, are surely avoided inasmuch as $f_{Nyquist}$ = 12.5 kHz.

A random signal usually has a finite average power and therefore, can be characterized by an average power spectral density [16]. The power spectral density (PSD) of a time series $y(t)$ describes how the variance of the data is distributed over the frequency components into which $y(t)$ may be decomposed. Our motivation for considering spectral analysis is to characterize the average power at frequency ω in the signal, given by the formula:

$$\varphi(\omega) = \lim_{N \to \infty} E \left\{ \frac{1}{N} \left| \sum_{t=1}^{N} y(t) e^{-i\omega t} \right|^2 \right\} \tag{5}$$

where

$1/N$ – normalization parameter by N number of points of the available data sequence.

$\varphi(\omega)$ is a periodic function, with the period equal to 2π. Hence, $\varphi(\omega)$ is completely described by its variation in the interval:

$$\omega \in [-\pi, \pi] \text{ (radians per sampling interval)} \tag{6}$$

Alternatively, the PSD can be viewed as a function of the frequency:

$$f = \frac{\omega}{2\pi} \quad \text{(cycles per sampling interval)} \tag{7}$$

Then, from a finite-length record $\{y(1), \ldots, y(N)\}$ of a second-order stationary random process, the premise of our problem is to determine an estimator $\hat{\varphi}(\omega)$ of its power spectral density $\varphi(\omega)$, for ω $[-\pi, \pi]$.

4.2. Spectral estimator, Welch's method

The use of Fast Fourier Transform for the estimation of the power spectrum is a well known technique. A more practical approach is the Discrete-Time Fourier Transform (DTFT). Various improvements have been proposed over the years. For this research, averaged periodograms of overlapped, windowed segments of a time series algorithm, using the so-called Welch's method was implemented. A periodogram here means the DTFT of one segment of the time series, while modified refers to the application of a time-domain window function and averaging to reduce the variance of the spectral estimates is used.

Motivated by the high variance of the periodogram and based on Bartlett's method, Welch's method, represents an improvement used for estimating the power of a signal at different frequencies. The signal is split up into overlapping segments. *L* data segments of length *M*, overlapping by *D* points [17]. The overlapping segments are then windowed. After setting these parameters, the squared magnitude of each segment is computed and time-averaged – this reduces the variance of the individual power measurements, at the cost of reduced resolution. Furthermore, the 95% confidence intervals are calculated and indicated with the grey area called the 'healthy region'.

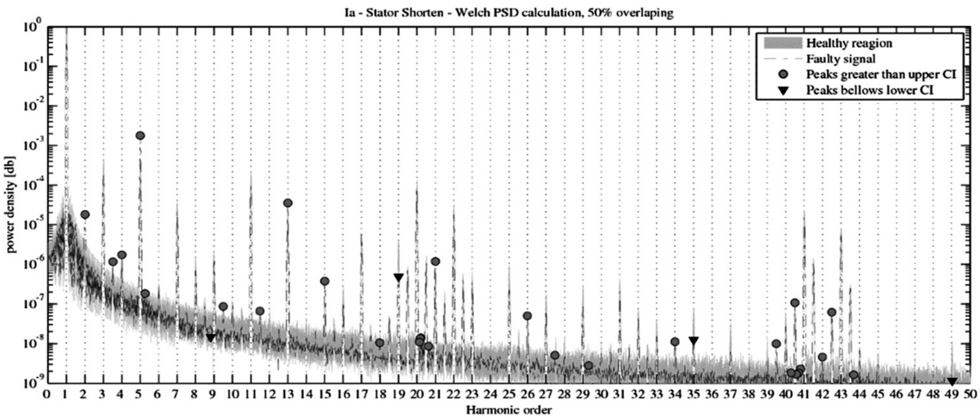

Fig. 3. Power spectral density under fault condition: Stator shorten

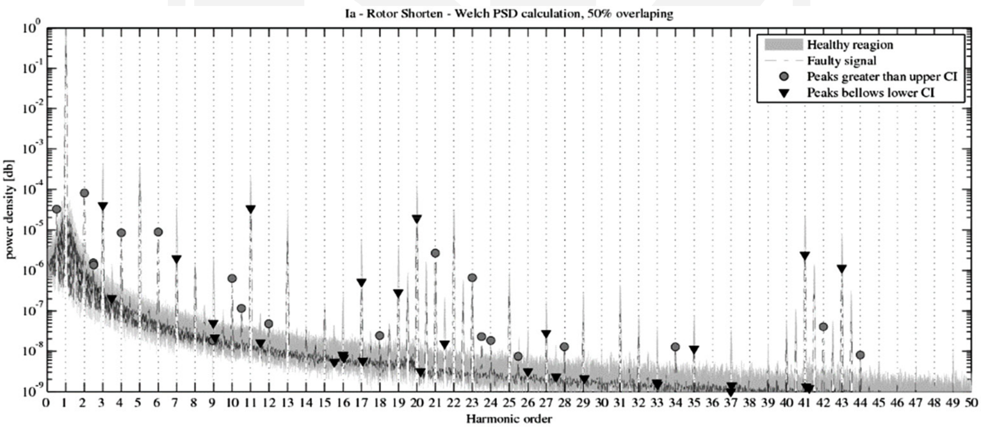

Fig. 4. Power spectral density under fault condition: Rotor shorten

As it is possible to see from Figs. 3 and 4, the PSD of the faulty signal is represented over the healthy region defined by a 95% confidence interval. The peaks greater than the upper confidence interval and below the lower interval are indicated at their respective frequency.

5. Results

In general, properly designed electrical machines and no fault condition, it is expected to have a symmetrical flux distribution in the air gap. All machines have constructional asymmetries. In fact, these asymmetries, have already been exploited to perform fault detection. Consequently, the magnetic field distribution will be affected.

Using the healthy synchronous machine spectrum as a reference, it seems logical to assume that if the amplitude of the measured faulty signals is located outside the confidence intervals, the machine is no longer operating under a symmetrical state. Therefore, a fault condition is detected. When a difference is detected in a particular frequency, and the variations found are not as significant, the level of uncertainty is higher than that established by the confidence intervals.

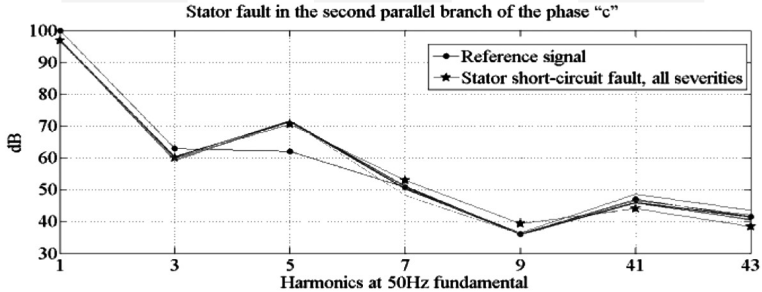

Fig. 5. Stator current harmonics for fault in a parallel branch of the stator winding

In Figure 5, the first odd harmonics and stator-harmonics for the stator fault in the second parallel branch of phase 'c' is presented (See Fig. 1). In Figure 5, it is easy to identify the appearance of a higher peak at 250 Hz for all level off fault. The variation detected is only 10 dB. Therefore, looking at all harmonics levels, it is possible to understand how the amplitude remains constant and under different short-circuit severities for all harmonics with the exception of the fifth harmonic.

Looking at the spectra of the motor running with a fault in the rotor (Fig. 4) it is possible to appreciate how the even harmonics show greater peaks than the upper bound of the machine running on the healthy state. More meaningful are the two side peaks that appear at 25 Hz and 75 Hz.

6. Conclusions

One of the aims of the extended research on Multicriteria diagnosis of synchronous machines is to use available tools in order to identify the associated variables related to faults in the system. This paper has shown how it is possible to on-line detect slow rising short-circuits in the stator and/or rotor by only using a basic data acquisition card connected to a standard PC/laptop using the spectrum of the healthy machine as a reference.

Using Welch's method, it was possible to quantify and determine the variation of the energy around a frequency-bin.

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