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Fault Detection (Condition Monitoring) of Induction Motor based on Wavelet Transform

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Abstract - Presently, many condition monitoring techniques that are based on steady-state analysis are being applied to Induction motor. However, the operation of induction motor is predominantly transient, therefore prompting the development of non-stationary techniques for fault detection. In this paper we apply steady-state techniques e.g. Motor Current Signatures Analysis (MCSA) and the Extended Park's Vector Approach (EPVA), as well as a new transient technique that is a combination of the EPVA, the Discrete Wavelet Transform and statistics, to the detection of turn faults in a induction motor. It will be shown that steady-state techniques are not effective when applied to induction motor operating under transient conditions. The new technique shows that stator turn faults can be unambiguously detected under transient conditions.

I. INTRODUCTION

There are many techniques and tools available, which are used to monitor the condition of these machines, thus prolonging their life span. Some of the technology used for monitoring includes sensors, which may measure speed, output torque, vibrations, temperature, flux densities, etc. These sensors are together coupled with algorithms and architectures, which allows for efficient monitoring of the machines condition [2]. The most popular methods of induction machine condition monitoring utilize the steady-state spectral components of the stator quantities [3]. These stator spectral components can include voltage, current and power and are used to detect turn faults, broken rotor bars, bearing failures, air gap eccentricities. Presently, many techniques that are based on steady-state analysis are being applied to Induction motor. However, the operation of induction motor is predominantly transient, therefore prompting the development of non stationary techniques for fault detection.

In this paper we apply steady-state techniques e.g. Motor Current Signatures Analysis (MCSA) and the Extended Park's Vector Approach (EPVA), as well as a new transient technique that is a combination of the EPVA, the Discrete Wavelet Transform and statistics, to the detection of turn faults in a three phase induction motor. It will be shown that steady-state techniques are not effective when applied to induction motor operating under transient conditions. The new technique shows

that stator turn faults can be unambiguously detected under transient conditions.

II. PRACTICAL TECHNIQUE TO SIMULATE AN INTER-TURN FAULT OF A STATOR PHASE WINDING

An inter-turn fault of a stator phase winding is a result of the deterioration of insulation between the individual coils. This is in essence a short circuit of the stator phase winding, which changes the symmetrical stator current to one that is asymmetrical. For predicting the electrical behavior from the stator supply due to an inter-turn fault, it would appear that the impedance of the short-circuited stator winding has decreased. The degree to which its impedance has decreased depends on the severity of the fault. To simulate the inter-turn fault on the induction motor, the impedance of the stator phase winding is decreased by placing a resistor in parallel with the winding, as shown in Fig. 2 [1-2].

Figure 2 : Simulation of the tum fault

III. EXPERIMENTAL RESULTS

The experimental results show the induction motor operating in steady-state and transient conditions. The steady-state results show the motor operating at rated stator current. The transient captured shows the current changes as speed increases from 1120 rpm to 1460 rpm over 5 seconds and is shown in figure 3. This illustrates the ability of the system to operate within subsynchronous and super-synchronous regions, since the synchronous speed is 1500rpm. For each of the speed conditions, the machine was operated under three health conditions. The first condition illustrates the machine operating without any faults placed on the machine. The next two conditions illustrate the simulated inter-turn fault placed on one stator phase winding.

The three non-invasive diagnostic techniques used to identify the inter-turn fault include Motor Current Signature Analysis (MCSA), The Extended Park's Vector Approach (EPVA) and the Discrete Wavelet Transform (DWT).

A. Motor Current Signature Analysis

The most popular methods of induction machine condition monitoring utilize the steady-state spectral components of the stator quantities. These spectral components can include voltage, current and power and can be used to detect broken rotor bars, bearing failures, air gap eccentricity etc. The accuracy of these techniques depend on the loading of the machine, the signal to noise ratio of the spectral components being examined and the ability to maintain a constant current to facilitate fault detection [2].

The objective of the Motor Current Signature Analysis is to identify the stator current spectral components that are characteristic of inter-turn stator faults. Equation (1) indicates the frequency components that are characteristic of shorted turns [3].

$$f_{st} = f_1 \left[\frac{n}{p} (1-s) \pm k \right] \quad (1)$$

where, f_{st} = stator frequency components that are a function of shorted turns, f = supply frequency, $n = 1, 2, 3, \dots$, $k = 1, 3, 5, \dots$, p = pole-pairs, s = slip

As shown in (1), the inter-turn fault frequency components are dependant upon slip. During transient conditions there are change s in speed. The frequency components are therefore continuously changing and identifying these frequencies becomes an extremely difficult task.

Using the Fast Fourier Transform (FFT), a frequency spectrum of the stator current is shown and

examined, for a induction motor operating at a constant speed and a speed change from synchronous to subsynchronous. Figure 4 shows the stator current spectrum for the machine operating at a constant speed of 1460 rpm. During the inter turn fault conditions, there appears to be a new current component existing around 124.7Hz, which corresponds to the theoretical predictions as given by (1), with $n=4$ and $k=1$. Figure 5 shows the current spectrum during the transient response. Although there seems to be components at 124.7Hz, this could be misinterpreted because the slip has changed and these frequencies should be present.

Figure 3. Spectrum of stator currents for constant subsynchronous speed operation.

Figure 4. Spectrum of stator currents for operation through synchronous operation.

IV. WAVELET ANALYSIS

Since the previous methodology has weakness when the system is transient, we therefore proposed the use of wavelets to produce a similar analogy to that of the steady state severity factor. The methodology

employed is to decompose the non-stationary EPVA magnitude signal into both detail and approximate coefficients at different scales using Daubechies wavelets. The detail coefficients are then examined to determine the fault severity.

A signal can be decomposed into approximate coefficients, $a_{j,k}$, through the inner product of the original signal at scale j and the scaling function.

$$a_{j,k} = \int_{-\infty}^{\infty} f_j(t) \cdot \phi_{j,k}(t) dt = 0$$

$$\phi_{j,k}(t) = 2^{-j/2} \phi(2^{-j}t - k)$$

Similarly the detail coefficients, $d_{j,k}$ can be obtained though the inner product of the signal and the complex conjugate of the wavelet function.

$$d_{j,k}(t) = \int_{-\infty}^{\infty} f_j(t) \cdot \psi_{j,k}^*(t) dt$$

$$\psi_{j,k}(t) = 2^{-j/2} \psi(2^{-j}t - k)$$

The EPVA hints that the frequencies of interest, when determining turn faults, are twice the fundamental frequency. However these frequencies could shift during transients. It therefore makes sense to want to observe a band of frequencies rather than a single. The fundamental frequency of the stator is about 50Hz and therefore the frequencies of interest should be found around 100Hz. Using these clues we should be able to determine the scale of the detail level that will contain the coefficients that encode these frequencies. The sampling frequency of the signals is 5000Hz. It is therefore evident that the bandwidth captured is 2500Hz.

We can now divide this bandwidth into scale levels knowing that the bandwidth is halved after each scale.

From table 1 we can see that a 100Hz signal will be encoded by the detail coefficients of scale 5, (d5), and therefore this is the detail level of interest. When comparing the wavelet decomposition for a damaged and undamaged machine, a difference can be seen in detail levels d4, d5 and d6. However the most significant difference can be seen in d5 as shown in figures

It is therefore clear that d5 should be used in some kind of diagnostic algorithm. In the experiments performed, the speed of the machine was changed from 1170-1500, 1170-1970, 1400-1720 and 1640-1970rpm. The motivation for this is that the diagnostic method should not be affected by speed or slip changes as with steady-state analysis.

Scale	Bandwidth (Hz)
d1	1250-2500
d2	625-1250
d3	312-625
d4	156-312
d5	78-156
d6	39-78
d7	19-39

TABLE I. THE BANDWIDTH REPRESENTED BY EACH SCALE.

When observing the coefficients of d5 for each transient, it was found to be an extremely difficult task to correlate the coefficients in the damaged machine to that of the healthy machine at all speed changes. For this reason a statistical approach was attempted. Generating a histogram of the d5 coefficients has shown to give a better insight into the machine's condition. In the case of a healthy machine the coefficients produce a gaussian distribution as shown in figure. In the case of the damaged machine, the distribution is bimodal as shown in figure 16. These distribution plots are especially useful when unambiguously determining if a machine is healthy. The EPVA method will always have an amplitude at twice the fundamental frequency, and depends on the DC component for a severity factor. These results can be misinterpreted if the DC component varies with time as in the case with induction motor. However in these distribution plots, the healthy condition is only indicated by the gaussian shape of the distribution. The same principle applies to a damaged machine. The bimodal shape is indicative of the turn fault.

The distribution of the d5 coefficients at different speed changes.
(Healthy Machine).

The distribution of the d5 coefficients at different speed changes.
(Damaged Machine).

V. CONCLUSIONS

Wavelet analysis has been successfully applied to the detection of stator turn faults in doubly-fed induction generators found in wind turbines. The detection algorithm is a combination of the Extended Park's Vector, wavelet analysis and statistics. This technique is not affected by changes in the speed of the machine which is crucial when applied to wind generators.

The 5 detail scale has been identified for use in the analysis. It has been found that the order of the wavelet used is not crucial, in fact the simplest wavelet, i.e. Haar wavelet, can be used to successfully detect the turn fault.

The coefficient distribution for the 5 detail scale is Gaussian when there are no turn faults. The distribution is bimodal with a flattened interior when the turn faults are present.

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