Wavelet Analysis and Park's Vector Based Condition Monitoring of Induction Machines

HARLIŞCA Ciprian, SZABÓ Loránd

Technical University of Cluj-Napoca, Romania
Department of Electrical Machines and Drives,
400114 Cluj-Napoca, Memorandumului 28, Romania; e-mail: Ciprian.Harlisca@mae.utcluj.ro

***Abstract* – Condition monitoring is an important issue in the maintenance of electrical machines. In the last years many methods of fault detection were cited in literature. Most of the newly proposed advanced methods are for on-line and non-invasive monitoring. This means that the faults can be detected already in their incipient phase during the usual work of the monitored machines. The aims of this paper is to make a brief review of two nowadays more and more frequently used induction machines' fault detection practices: the wavelet analysis based method and the Park's vector approach.**

***Keywords:* induction machines; diagnosis; fault detection; condition monitoring; wavelet analysis; Park's vector.**

I. INTRODUCTION

Squirrel cage induction machines are widely used in modern industry applications due to their robustness, low cost, and easy maintenance.

Many of its basic components are susceptible to failure. The faults occur in most of the cases in bearings or shafts, stator windings and rotor bars. However, by means of advanced on-line diagnosis methods it is possible to detect the faults in their incipient phase, before the catastrophic effects of the failures on the machine which can cause long time downtimes and huge costs in industrial environment [1].

About 40% of the faults that occur in induction machines are in the bearings, 30 to 40% in the stator, 10% in the rotor and the remaining ones in the auxiliary devices of the machine [2].

Condition monitoring of induction motor requires wide range multidisciplinary knowledge, therefore it is a challenging topics for numerous engineers working in various fields.

Many condition monitoring methods are cited in the literature, including vibration, thermal, chemical and acoustic emission monitoring. Unfortunately all these methods require expensive sensors or specialized tools. Therefore the widely used current monitoring methods have a main advantage over those mentioned above: they require only (frequently already existing) simple and cheap current sensors.

The current monitoring based techniques can be used to detect almost all of the faults of a squirrel cage induction machine: rotor bar faults, shorted winding fault, air-gap eccentricity faults, bearing faults, load faults, etc. This method is non-intrusive and can be applied both on-line and in a remotely controlled way.

In the paper two of the most frequently used current monitoring methods used in condition monitoring of the squirrel cage induction machines are overviewed.

II. WAVELET ANALYSIS BASED MONITORING

By its basic definition a wavelet is a particular wave whose energy is concentrated in a specific temporal location. It can be considered as a known signal with some peculiar characteristics. It can be easily used in studying the properties of other signals simultaneously in the frequency and time domains. A typical plot of a wavelet is given in Fig. 1.

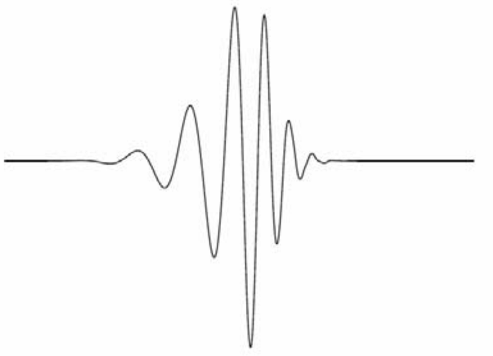

Fig. 1. A typical plot of a wavelet

A wavelet is an oscillation similar to that recorded by a seismograph or a heart monitor. Its amplitude starts out at zero, increases and then decreases back to zero. There are a variety of wavelets that have specific properties, and can be used for signal analysis in various fields of sciences, as computer imaging, climate analysis, heart monitoring, seismic signal denoising, audio and video compression, fast solution of partial differential equations, etc., but also in condition monitoring of rotating machines [3].

There are several common families of wavelets:

- Wavelets for Continuous Wavelet Transform (Gaussian, Morlet, Mexican Hat, etc.)
- Daubechies Maxflat Wavelets
- Symlets
- Coiflets
- Biorthogonal Spline Wavelets
- Complex Wavelets

The most typical wavelet types used in condition monitoring of electrical machines are given in Fig. 2.

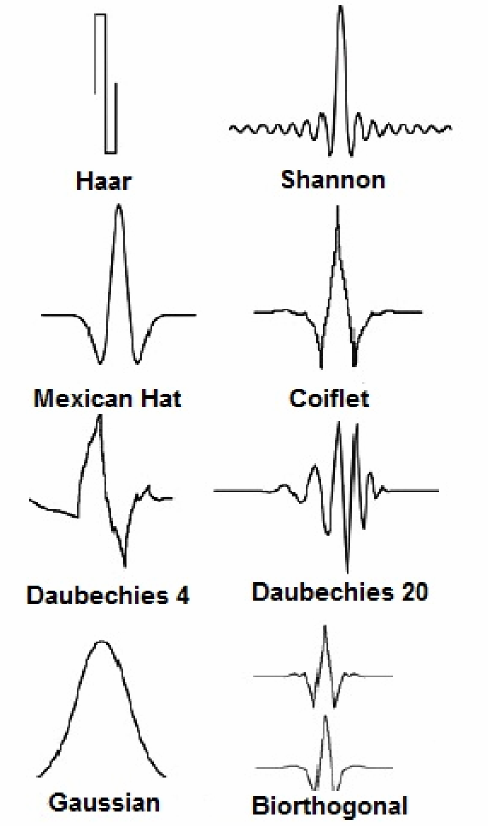

Fig. 2. The most typical wavelet types

The Fourier transform is widely used since several years in fault diagnosis and condition monitoring, but it has several drawbacks. It gives excellent results if the analyzed signal is stationary or periodic, but is not appropriate for a signal that has transitory characteristics such as drifts, abrupt changes and frequency trends [4].

The wavelet transform was introduced with the idea of overcoming the drawbacks of the Fourier transform. The wavelet transform assures both time-frequency analysis and time scale analysis with multiresolution characteristic.

Due to all these advantages it can be very useful in the fault detection of electrical machines working in frequently existing variable load applications [5].

The Fourier transform decomposes a signal to complex exponential functions of different frequencies. This is defined by the following equation [6]:

$$X(f)=\int_{-\infty}^{+\infty} x(t)\cdot e^{-2j\pi ft}dt \tag{1}$$

where f is the frequency, t the time and x is the analyzed signal.

In short time Fourier transform (STFT) the signal to be processed is divided into small segments, which can be assumed to be stationary. For this purpose a window function is chosen.

The expression of the STFT is the following [6]:

$$STFT_x^{\omega(t)}(t,f)=\int_t \left[x(t)\omega^*(t-t')\right]\cdot e^{-j2\pi ft}dt \tag{2}$$

where $\omega(t)$ is the window function and * marks the complex conjugate.

Fourier analysis consists of decomposing a signal into sine waves of different frequencies. In a similar way, wavelet analysis is the breaking up of a signal to a shifted and scaled version of the original wavelet, also known as mother wavelet [7].

The scaling of a wavelet means stretching (or compressing) it, while the shifting is the delaying (or hastening) its onset [8].

If the scale of a wavelet is high, results that it corresponds to a low frequency stretched wavelet. If it is low, it corresponds to a high frequency compressed wavelet. The smaller scale factor corresponds to a more compressed wavelet [9].

In the analysis of the starting current of an induction machine, two types of wavelet transform, continuous wavelet transform (CWT) and discrete wavelet transform (DWT) can be used [10].

The continuous wavelet transform was developed to overcome the resolution problem of the short time Fourier transform. The wavelet analysis is very similar to that of the STFT analysis. In both cases the signal is multiplied with a function, a wavelet in the case of wavelet analysis and window function in the STFT, also the transform is computed separately for different segments of the time-domain signal.

The CWT is defined by the following equation [6]:

$$CWT_x^{\omega(t)}(t,f)=\Psi_x^{\psi}(\tau,s)=\frac{1}{\sqrt{|s|}}\int x(t)\psi^*(\frac{t-\tau}{s})dt \tag{3}$$

where τ and s are the translation and scale parameters, $\psi(t)$ is the transforming function, also called the mother wavelet.

If the discrete wavelet transform is used, the signal is analyzed at different frequency bands with different resolutions in order to decompose the signal into a coarse approximation and detail information. This is done by using digital filtering techniques. The signal is passed through high pass filters to analyze the high frequencies and through low pass filters to analyze the low frequencies [6].

The DWT associates low pass and high pass filters with two sets of functions, called scaling functions and wavelet functions, as shown in Fig. 3.

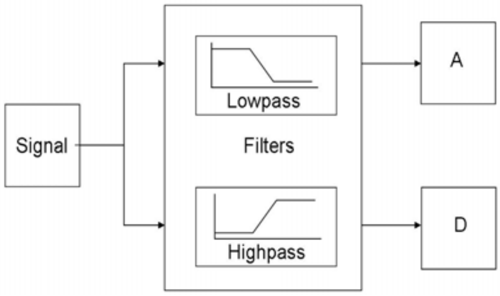

Fig. 3. The filtering of the signal by means of DWT

The decomposition of the signal to be analyzed into different frequency bands is obtained by successive high pass and low pass filtering of the time domain signal (see a two-levels decomposition in Fig. 4).

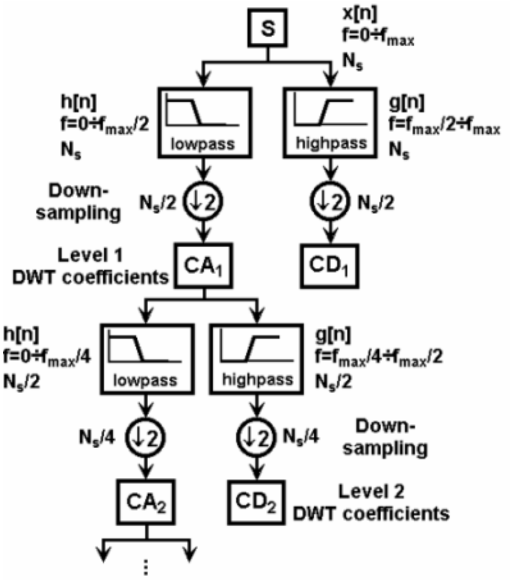

Fig. 4. Two levels decomposition of the signal

The wavelet based detection methods have good sensitivity in detecting faults. They assure short fault detection time and can be easily applied also in on-line and remote condition monitoring of electrical machines.

Wavelets can be used to examine signals simultaneously in both time and frequency.

III. PARK'S VECTOR APPROACH

One of the difficulties met in the analysis description of the behavior of most rotating electric machines is that the inductances are function of the relative position of the rotor and stator.

In order to simplify the study of the electrical machines R.H. Park developed a transformation that made their analysis more straightforward by transforming the motor equations into a two-phased orthogonal reference frame [11].

The transformation of the three-phased system to the two-phased orthogonal one can be performed upon:

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \left[P_{dq0}\right] \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{4}$$

where f is the function to be transformed (it can be the current, voltage or magnetic flux). The Park transformation matrix is:

$$\left|P_{dq0}\right| = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{5}$$

$\theta = \omega t$ being the angular displacement.

By using the above transformation the orthogonal components of the Park's current vector can be computed from the symmetrical three-phased current system, having the components: i_a, i_b and i_c:

$$\begin{aligned} i_d &= \sqrt{\frac{2}{3}}\left[i_a \cos\theta + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \\ i_q &= -\sqrt{\frac{2}{3}}\left[i_a \sin\theta + i_b \sin\left(\theta - \frac{2\pi}{3}\right) + i_c \sin\left(\theta + \frac{2\pi}{3}\right)\right] \end{aligned} \tag{6}$$

If the reference is fixed in the stator of the machine ($\theta = 0$) the above equation becomes:

$$\begin{aligned} i_d &= i_a - \frac{i_b}{2} - \frac{i_c}{2} \\ i_q &= \frac{\sqrt{3}}{2}\left(i_b - i_c\right) \end{aligned} \tag{7}$$

When the induction machine if healthy its three-phased stator current system is perfectly symmetric:

$$\begin{aligned} i_a &= \sqrt{2} I \sin(\omega_s t) \\ i_b &= \sqrt{2} I \sin\left(\omega_s t + \frac{2\pi}{3}\right) \\ i_c &= \sqrt{2} I \sin\left(\omega_s t + \frac{4\pi}{3}\right) \end{aligned} \tag{8}$$

where I is the maximum value of the supply phase current, ω_s is the supply frequency and t is the time variable.

In this case by replacing (8) in (7) the following equation can be obtained for the two orthogonal components of Park's current vector in the case of a healthy electrical machine:

$$\begin{aligned} i_d &= \frac{3}{2} I \sin(\omega t) \\ i_q &= \frac{3}{2} I \cos(\omega t) \end{aligned} \tag{9}$$

Upon equation (9) it can be stated that that a healthy machine shows a perfect circle in Park's vector representation, as shown in Fig. 5.

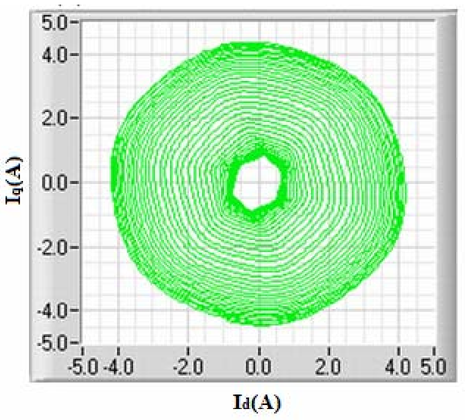

Fig. 5. The plot of Park’s current vector for a healthy machine during startup

When any type of fault occurs the three-phased current phase current system becomes unbalanced. This result in an elliptic representation of the Par k's current vector (see Fig. 6).

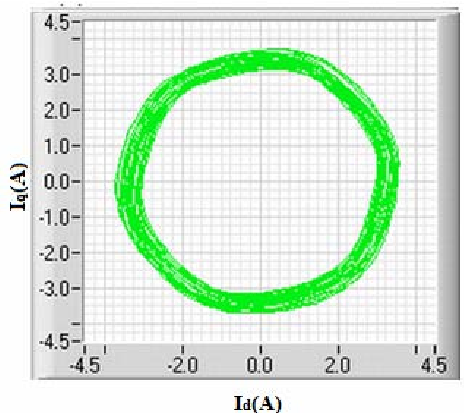

Fig. 6. The plot of Park’s current vector
for a faulty machine in steady-state regime

The Park's vector based approach is widely used in the diagnosis of most common faults of the squirrel cage induction machines.

From the parameters of the ellipse the fault's gravity can be established. If the severity of the fault increases, the elliptical form of the representation will be more highlighted [13].

If this method is used alone it encounters difficulties in isolating different faults of the squirrel cage induction machine, because different faults may cause a similar deviation in the Park’s vector. Unfortunately it cannot distinguish the effects of the non-symmetries of the feeding voltage or of the machine itself not connected to the faults.

IV. CONCLUSIONS

The presented methods are non-invasive fault detection techniques. Compared with Fourier transform based methods the two methods in discussion can detect faults even in electrical machines with a light or variable load.

Both detailed methods allow continuous real-time tracking of various types of faults in squirrel cage induction motors operating under continuous stationary and non-stationary conditions. These recognize the fault signatures produced by the electrical machine and can estimate the severity of the faults under different load conditions.

ACKNOWLEDGMENT

This paper was supported by the project "Improvement of the doctoral studies quality in engineering science for development of the knowledge based society-QDOC" contract no. POSDRU/107/1.5/ S/78534, project co-funded by the European Social Fund through the Sectorial Operational Program Human Resources 2007-2013.

REFERENCES

[1] M.E.H. Benbouzid, "A Review of Induction Motors Signature Analysis as a Medium for Faults Detection", IEEE Transactions on Industrial Electronics, vol. 47, no. 5 (October 2000), pp. 984-993.

[2] Motor Reliability Working Group, "Report of large motor reliability survey of industrial and commercial installations Part I, and II", IEEE Transactions on Industry Applications, vol. IA21, no. 4 (July 1985), pp. 853-872.

[3] K.P. Soman, K.I. Ramachandran and N.G. Resmi, "Insight into Wavelets from Theory to Practice", Prentice-Hall of India, 2008.

[4] A.A. da Silva and B.R. Upadhayaya, "Rotating Machinery Monitoring and Diagnosis Using Short-Time Fourier Transform and Wavelet Techniques", in Proc. of the 1997 International Conference on Maintenance and Reliability, Knoxville (USA), vol. 1, pp. 14.01-14.15, 1997.

[5] H. Douglas, P. Pillay and A. Ziarani, "Detection of Broken Rotor Bars in Induction Motors using Wavelet Analysis", Proc. of the IEEE International Electric Machines and Drives Conference (IEMDC '03), vol. 2, pp. 923-928, 2003.

[6] L. Szabó, J.B. Dobai and K.Á. Bíró, "Discrete Wavelet Transform Based Rotor Faults Detection Method for Induction Machines", Intelligent Systems at the Service of Mankind, vol. 2., (eds: W. Elmenreich, J.T. Machado, I.J. Rudas), Ubooks, Augsburg (Germany), pp. 63-74, 2005.

[7] N. Mehala and R. Dahiya, "Rotor Fault Detection in Induction Motor by Wavelet Analysis", International Journal of Engineering, Science and Technology, vol. 1, no. 3, pp. 90-99, 2008.

[8] M. Misiti, Y. Misiti, G. Oppenheim and J. M. Poggi, "Wavelet Toolbox Users Guide", Version 1, The Mathworks, Inc., 1996.

[9] S.K. Ahmed, S. Karmakar, M. Mitra and S. Sengupta, "Diagnosis of Induction Motors Faults due to Broken Rotor Bars and Rotor Mass Unbalance through Discrete Wavelet Transform of Starting Current at No-Load", J. of Electrical Systems, vol. 6, no. 3, pp. 442-456, 2010.

[10] R.S. Arashloo and A. Jalilian, "Induction Motor Broken Rotor Bar Faults Using Discrete Wavelet Transform", 24th International Power System Conference, 2009.

[11] C. Laughman, S. Leeb, L. Norfold, S. Shaw and P. Armstrong, "A Park Transform-Based Method for Condition Monitoring of 3-Phase Electromechanical Systems", Mitsubishi Electric Research Laboratories, May 2010.

[12] H. Nejjari and M.E.H. Benbouzid, "Condition Monitoring and Diagnosis of Induction Motors Electrical Faults Using a Park’s Vector Pattern Learning Approach", IEEE Transactions on Industrial Application, vol. 36, no. 3 (May/June 2000), pp. 730-735.

[13] L. Szabó, E. Kovács, F. Tóth and G. Fekete, "Rotor Faults Detection Method for Squirrel Cage Induction Machines Based on Park’s Vector Approach", Oradea University Annals , Electrotechnical Fascicle, Computer Science and Control Systems Session, pp. 234-329, 2007.

[14] N. Mehala and R. Dahiya, "Detection of Bearing Faults on Induction Motor Using Park's Vector Approach", International Journal of Engineering and Technology, vol. 1, no. 3, pp. 90-99, 2010.

[15] C.J. Verucchi, G.G. Acosta and F.A. Benger, "A Review on Fault Diagnosis of Induction Machines", Latin American Applied Research, vol. 38 no. 2, pp. 113-121, 2008.