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Jose A. ANTONINO-DAVIU*, Jan RUSEK**, M. RIERA-GUASP*, Jose ROGER-FOLCH*

TRADITIONAL VERSUS WAVELETS LOW-PASS FILTERING IN DIAGNOSING OF CAGE ASYMMETRIES IN INDUCTION MACHINES***

SUMMARY

The paper deals with the diagnosis of squirrel cage asymmetries in induction machines. The results of practical measurements and analyses for two different cases are included. The first case refers to a 400 kW industrial induction machine and the second one to a 1.1 kW laboratory induction motor. In both cases the rotor cages are concluded to possess broken bars. Two different diagnostic approaches are employed. The first or traditional one is the digital low pass filtering. The other or more modern one is the wavelet decomposition. Both approaches were found to be viable, although the latter one shows some potential advantages over the previous one, especially if in future more diagnostic harmonics should be accounted for.

***Keywords**: induction motors, diagnostics, low-pass filtering, wavelet transform*

PORÓWNANIE FILTROWANIA TRADYCYJNEGO I FALKOWEGO W DIAGNOSTYCE NIESYMETRII KLATKI MASZYN INDUKCYJNYCH

Artykuł dotyczy diagnozowania stanu klatek silników indukcyjnych klatkowych. Podano wyniki pomiarów i analiz dwóch rzeczywistych maszyn. Przypadek pierwszy dotyczy maszyny o mocy 400 kW a drugi o mocy 1,1 kW. W obu przypadkach wyniki analiz diagnostycznych wskazują na obecność przerwanych prętów w klatkach ich wirników. Analizy diagnostyczne wykonano dwoma metodami. Pierwsza polegała na zastosowaniu tradycyjnego cyfrowego filtrowania dolnoprzepustowego. Druga, nowoczesna, polegała na zastosowaniu dekompozycji falkowej. Stwierdzono, że choć obydwa podejścia były skuteczne, to jednak analiza diagnostyka bazująca na analizie falkowej wnosi perspektywicznie większe możliwości, zwłaszcza jeśli w przyszłości diagnostyka bazować będzie na kilku a nie, jak dotychczas, jednej harmonicznej.

***Słowa kluczowe**: silniki indukcyjne, diagnostyka, filtrowanie dolnoprzepustowe, transformacja falkowa*

1. INTRODUCTION

Squirrel cage induction machines constitute critical elements of many industrial applications. Their failure can cause high wastes in time and money, a fact that many companies can not afford. The failure of the induction machine can appear in its many constituent elements, such as bearings, insulation, clutch and stator or rotor windings. Cage asymmetries constitute a non-negligible percentage among all the faults feasible to take place in those machines. Identification of incipient failures is an objective of the diagnosis, contributed by a growing number of the results of scientific researches.

The startup conditions were proposed by many researchers as a proper base for cage state diagnosis, especially when the diagnoses should be based on supply currents. It turns out that the growing rotor speed is accompanied by changing frequency of the main diagnostic component (left sideband component) with frequency given by

$$f_{S2} = (1-2s) \cdot f_0 \qquad (1)$$

where f_0 is the supply frequency and s is the slip.

It follows from (1) that in the vicinity of half of the full speed the frequency of this stator current component is low, and even falls down to zero at exactly half of the synchronous speed. Traditional technique of identification of this component relies in low pass filtering. Early versions of diagnostic systems used the analogical filters to achieve the identification of this component. Contemporary diagnostic systems use exclusively digital low pass filters, whereby the currents are registered with analog-digital converters installed as separate units or onboard of the portable computers. The low pass filtering itself is usually accomplished thereafter, that is offline [1].

The other, much more contemporary, approach is based on the application of the Discrete Wavelet Transform to discern the left sideband component in the stator current during starting up, whereby this component changes both the amplitude and the frequency. The main advantage of this already well founded signal-analysis tool is the automatic filtering performed by the wavelets signals [2], which allows to extract the time evolution of the frequency components of the original signal within their associated frequency bands.

Application of Wavelet Transform is not restricted to the analysis of startup current. In [3] the efficiency of this method was demonstrated also with respect to the steady state currents, received from both the simulations and measurements. It has to be stressed that in [3] the calculations were based on a dynamical model in which the inductances were determined via making use of both the winding and air-gap functions. Thus it was possible to account for slotting.

* Universidad Politecnica de Valencia, Department of Electrical Engineering, Spain
** AGH University of Science and Technology, Department of Electrical Machines in Cracow, Kraków
*** Artykuł uzyskał pozytywne recenzje i był prezentowany podczas MIędzynarodowego Sympozjum Maszyn Elektrycznych SME 2006 w Krakowie

However, the most fruitful application of the Wavelet Transform is in the analysis of the startup current. The results of simulation and laboratory tests presented in [4–6] proved the efficiency of the wavelet decomposition of the startup current for the diagnosis of rotor cage asymmetries. It was stressed that, once the electromagnetic transient is over, there is a clear difference between the current decomposition for the healthy and faulty machine.

In [7] it was proposed to test the cage integrity via survey of the startup torque. The rationale for this is that in the startup conditions the currents are big, resulting in that the bar breakages cause significant changes in cage currents distribution. This in turn gives rise of variable torque component, which can be easily identified via torque measurement. The advantage of this startup based diagnosis relies in that it does not require loading equipment, thus making it applicable also in manufacturer or reparation workshop conditions. The measured torque reveals its low-frequency component when the rotor speed approaches its rated value.

The methods developed for diagnostic purposes find application also in detecting ailments in the load. For example in [8] the effect of gearbox backlash increase due to teeth wears and teeth breakage on the stator current was investigated. It allowed concluding that the stator current spectrum delivers convenient base for gearbox diagnosis. In [9] and [10] it was demonstrated that the diagnostic methods are applicable also for converter fed induction machines, despite magnified level of background harmonics.

On the whole, the startup current based diagnosis constitutes an alternative to the classical approach for broken bar detection, based on Fourier analysis of the steady-state currents. Some drawbacks of the traditional method, such as overlapping of the diagnostic component (1) by the closely laying 50 cps fundamental component, can be avoided by the new approach.

In the present paper two alternative ways developed by different research groups are presented. Both of them are based on the extraction of the left sideband component (1) during startup of the motor. The first approach is based on utilization of the digital filters which extract the evolution of the component under a predefined cut-off frequency of about 25 cps. The second method is based on the application of the Discrete Wavelet Transform to the stator current signal and the further study of the approximation signal whose associated frequency band contains the range of frequencies through which the left sideband varies. The methods are applied to two motors with different sizes: a 400 kW industrial motor and a 1.1 kW induction motor. The diagnoses prove the validity of both approaches, with acknowledgement for potential advantages contained in the wavelet approach.

2. LOW-PASS FILTERING DIAGNOSIS

A diagnostic system based on low pass filtering was elaborated. It relies on one digitally registered supply current. The current is captured in the secondary winding of current transformers, accessed via current clips [11]. The current clips voltage signal is delivered to the portable computer fitted with analog to digital converting card. The registered startup currents are stored on the disc and are then analyzed offline by the low-pass-filtering based diagnostic system. The system accounts for the correction characteristic resulting from the frequency transfer functions of the current transformer, passive current clips, low pass and anti-aliasing filter. The cut-off frequency assumed for low pass filtering was 25 cps.

Figure 1 shows the low-pass filtering of the startup current corresponding to a two pole pair, 400 kW, squirrel cage induction machine driving a coal mill fan. There it is shown the diagnosis signal reflecting the evolution of the left sideband component (1) below the cut-off frequency of the filter.

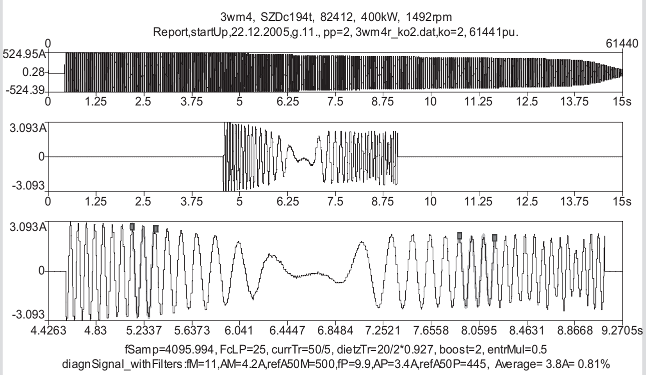

Fig. 1. Diagnostic report of the 400 kW machine, based on low pass filtering. (f_S = 4095.96 cps, f_C = 25 cps)

The sampling frequency was 4095.96 samples per second. It follows form Fig. 1 that the diagnostic signal of about 3 amps trespasses the half percent limit for the healthy cage. That is the machine is diagnosed as showing up cage asymmetry equivalent to at least one broken bar. In the semi automatically prepared diagnostic report, printed above and below the three plots, it can be read that the diagnostic signal amounts to 0.8 percent of the 50 cps or fundamental component. This value accounts also for the transmission characteristic of the whole measuring path. It consists of the current transformer, current clip sensors, anti- aliasing filter and entrance amplifiers. This characteristic, included into the digital diagnostic system, is automatically accounted for.

3. DIAGNOSIS USING THE DWT

The Discrete Wavelet Transform performs the decomposition of a sampled signal $\boldsymbol{s(t)}$ ($s_1, s_2, ..., s_N$) onto an approximation signal at a certain decomposition level n (a_n(t)) and n detail signals (d_j (t) with j varying from 1 to n). Each signal is the product of the corresponding coefficients (approximation coefficients for a_n and wavelet coefficients for d_j) and the scaling function or the wavelet function at each level, respectively. The signal then can be approximated as [2]

$$s(t) = \sum_i \alpha_i^n \cdot \varphi_i^n(t) + \sum_{j=1}^{n} \sum_i \beta_i^j \cdot \psi_i^j(t) = \\ = a_n + d_n + ... + d_1 \qquad (2)$$

Where α_i^n, β_i^j are the scaling and wavelet coefficients, respectively, $\boldsymbol{\varphi}^n(\mathbf{t})$, $\boldsymbol{\psi}^j(\mathbf{t})$ are the scaling function at level n and wavelet function at level j, respectively, and n is the decomposition level a_n is the approximation signal at level n and d_j is the detail signal at level j [2].

The practical procedure for the application of DWT is known as Mallat's algorithm or Subband coding algorithm. An analysis of this procedure shows that the approximation signal behaves as a low-pass filter whereas each detail signal behaves as a pass-band filter, extracting the time evolution of the components of the original signal included within its corresponding frequency band. If f_s (samples/s) is the sampling rate used for capturing $s(t)$, the detail d_j contains the information concerning the signal components whose frequencies are included in the interval $[2^{-(j+1)} \cdot f_s, 2^{-j} \cdot f_s]$. The approximation signal a_n includes the low frequency components of the signal, belonging to the interval $[0, 2^{-(n+1)} \cdot f_s]$.

The proposed approach is based on DWT decomposition of the startup current with further analysis of the approximation signal containing frequencies under the supply frequency. The DWT decomposition was done using the MATLAB Wavelet Toolbox. Daubechies-44 was considered for the analyses due to the convenience of using a high-order mother wavelet due to the non-ideal characteristic of the wavelet filters [5].

Figure 2 shows this approximation signal, resulting from the DWT analysis of the startup current for the 400 kW machine. Considering the sampling frequency of the signals (4096 samples/second) a 6-level decomposition was carried out. The frequency bands associated with the DWT signals are displayed in Table 1.

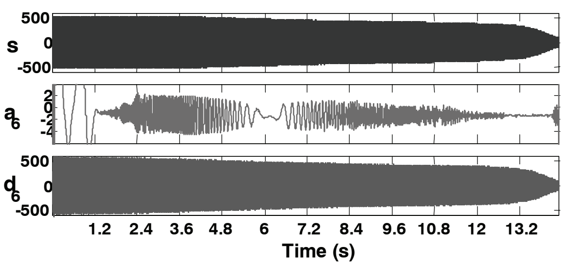

Fig. 2. Approximation signal resulting from the DWT for the 400 kW motor

Table 1

Frequency bands at each level

Level	Frequency band
d6	39.06–78.12 Hz
a6	0–39.06 Hz

The approximation signal would remain low if no rotor asymmetry existed in the machine. In Figure 2 the oscillations created by the asymmetry can be clearly seen. These oscillations are reflecting the evolution in amplitude and frequency of the sideband component associated with broken bars during the transient [6]. Thus, this signal can be used as a valuable tool for the diagnosis.

The amplitude of the diagnostic signal is bigger than that referring to at least one broken bar in the rotor cage. The characteristic shape of the diagnostic signal is plainly visible in the middle plot. From that plot it can also be concluded that at $t = 6$ seconds the rotor speed amounted exactly to 50% of the synchronous speed

The same approach was applied to a 4-pole, 1.1 kW induction motor coupled to a DC machine. A rotor bar break a hole in the selected bar. Main characteristics of the motor can be found in [5]. Figure 3 shows the approximation signal resulting from the DWT of the startup current for the unloaded machine with one broken bar. For this test the sampling frequency was 5000 samples/second. With this, the frequencies associated to the different wavelet signals are those shown in Table 2. The shape and magnitude of the approximation signal allows the diagnosis of the presence of the breakage also in this case.

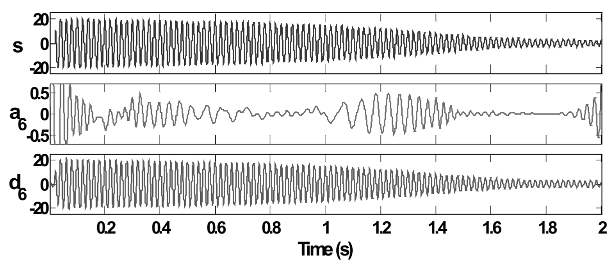

Fig. 3. Approximation signal resulting from the DWT for the 1.1 kW motor for one broken bar

Table 2

Frequency bands at each level

Level	Frequency band
d6	39.06–78.12 Hz
a6	0–39.06 Hz

Some indicators based on the energy of the wavelet signals have been proposed for quantifying the degree of severity of the fault. In [12] an indicator based on the energy of the approximation signal with associated frequency band containing components below the fundamental frequency was given. This indicator is given by (3).

$$I_{AF}\,(\mathrm{dB}) = 10 \cdot \log \left[\frac{\sum_{j=Nb}^{Ns} i_j^2}{\sum_{j=Nb}^{Ns} \left[a_{nf}(j) \right]^2} \right] \tag{3}$$

Where i_j is the value of the j sample of the current signal; $a_{nf}(j)$ is the j element of the order nf approximation signal (this is the approximation signal whose level is the same as that of the detail which contains the fundamental frequency (f)); N_s is the number of samples of the signal, until reaching the steady-state regime and N_b is the number of samples between the origin of the signals and the extinction of the oscillations due to border effect.

Computation of this indicator for the 1.1 kW induction motor in healthy state and in the motor with one bar breakage is shown in Table 3. There it is shown the clear difference in dB that arises between these two states, a fact that informs clearly about the presence of the breakage in the machine.

Table 3

Computation of the approximation signal indicator for healthy machine and machine with one broken bar

Status	$\sum_{i=NT}^{Ns} i^2(i)$	$\sum_{i=NT}^{Ns} \left[a_{nf}(i)\right]^2$	I_{AP} (db)	ΔI_{AP} (db)
Healthy	$8.9227 \cdot 10^5$	29.8495	**44.7556**	**–**
1 broken bar	$8.5379 \cdot 10^5$	251.4792	**35.3085**	**–9.447**

4. CONCLUSIONS

The diagnosis of the cage integrity, based on startup current, should be treated as valuable assistance of the diagnosis based on steady-state currents. This is due to the fact that the currents during startup trespass those in steady state, thus creating more optimal conditions for the exposure of the faulty cage elements.

Low pass filtering based procedures, despite their robustness, should be substituted by wavelet transform based procedures due to the potential advantages of the latter approach, especially if more diagnostic components should be accounted for. The aim of further work will be systematisation of the results that should allow developing a device for automatic discrimination between different types of faults.

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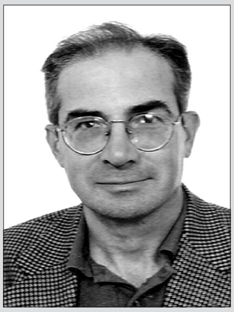
Jose A. ANTONINO-DAVIU

Received the M.Sc. degree in Electrical Engineering from the Polytechnic University of Valencia in 2000. He worked in the private sector, being involved in several international projects. Currently, he is Assistant Professor in the School of Industrial Engineering of the mentioned University, where he develops his docent and research work. He is currently pursuing the phD degree. His primary research interests are condition monitoring of electric machine, wavelet theory and its application to fault diagnosis and design and optimization of electrical installations and systems.

e-mail: joanda@die.upv.es



M. RIERA-GUASP

Received the M.Sc. degree in Industrial Engineering and the Ph.D. degree in Electrical Engineering from the Polytechnic University of Valencia (Spain) in 1981 and 1987, respectively. Currently he is an Associate Professor in the Department of Electrical Engineering of the Polytechnic University of Valencia. His research interests include condition monitoring of electrical machines, applications of the Wavelet Theory to electrical engineering and efficiency in electric power applications.

e-mail: mriera@die.upv.es

Jose ROGER-FOLCH

Obtained his M.Sc. degree in Electrical Engineering in 1970 from the Polytechnic University of Cataluna and his Ph.D in 1980 from the Polytechnic University of Valencia, Spain. From 1971 to 1978 he worked in the Electrical Industry as Project Engineer. Since 1978, he joined the Polytechnic University of Valencia and he is currently Professor of Electrical Installations and Machines. His main research areas are the Numerical Methods (F.E.M. and others) applied to the Design and Maintenance of Electrical Machines and Equipments.

e-mail: jroger@die.upv.es

Jan RUSEK

He works for the Chair of Electrical Machines of the AGH University of Science and Technology. He is involved in development of diagnostic-oriented models of squirrel cage induction machines. He is also involved in computer implementations of these models as well as of programs enhancing offline, current based, diagnosis of induction machines. Chair of Electrical Machines.

e-mail: gerusek@cyf-kr.edu.pl,