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Wavelet transform to induction motor analysis: review.

Transformada wavelet para análisis del motor de inducción: revisión.

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ABSTRACT

This study makes a revision of the most recent investigations that have implemented the wavelet transform by analyzing the electrical and mechanical variables of the induction motors. The investigations can be grouped into three main topics: diagnosis and detection of faults, control and detection systems and the classification of electromagnetic disturbances.

RESUMEN:

Este trabajo realiza una revisión de las investigaciones más recientes que han implementado la transformada wavelet analizando las variables eléctricas y mecánicas de los motores de inducción. Las investigaciones se pueden agrupar en tres temas principales: diagnóstico y detección de fallas; sistemas de control y detección y la clasificación de perturbaciones electromagnéticas.

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1. Introduction

The electrical actuators that contain three-phase induction motors are the more often used in the Industrial sector, it is estimate that the 70% of electrical energy that is used in industrial applications come from of induction motor [1] . The preference in respect to use it, is mainly because of the advantages that it presents in robustness, low cost, constructability, high reliability, minimum maintenance, among other ones.

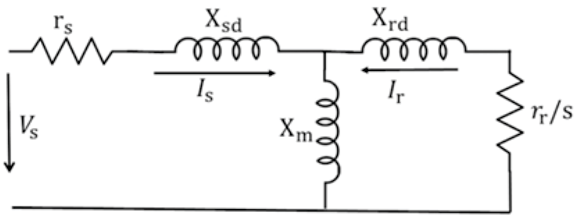

Figure 1. Equivalent electric circuit, per phase, of the model in permanent regime of the three-phase IM, for the single cage model, [2].

A lot of researches have been devoted to explain and grasped the mathematical relations of the mechanical and electrical variables that involve the operation of three-phase motor of induction (IM). For that purpose, it had been built different mathematical models that represent the performance in its variables. One of the commonly used is the simple cage with five parameters, which electric circuit equivalent is represented in [2]In this model the electric and mechanical variables the most interest are currents and voltages present in the stator, the speed and the torque on the shaft. The model parameters are the resistance of the stator *Xsd*,the reactance of the rotor *Xrd* and the magnetizing reactance *Xm*.

The variables: current, voltage, torque, and shaft speeds, are magnitudes that depends on time, usually called *Signals*. The performance of this signals provide information about functioning of the Three-phase motor of induction. The Fourier's transform, proposed by Jean Baptiste Joseph Fourier (1768-1830) and the Fourier's Transform in Short Times (FTST) by Denis Gabor (1900-1979) had been used widely for the signal analysis. To apply this transforms to a signal with domain in the time, it results a signal in the frequency domain, which present different properties very useful for Physical and engineering analysis.

In addition, to make an analysis about the frequency of a signal without regarding the variation in the time, or when the signal is invariant in the time, it means a stationary signal, for the situation it is useful the Fourier's transform. When it is want to analyze the signal in its domain of time and frequency, or the signal changes its frequency in the time, the signal is called non-stationary. In this cases it is used the FTST to make an analysis in a section of the signal to through a fixed time interval window. In the situation presented is not possible to analyze details of the variable frequency in different lengths of time intervals, since the window has an equal length for all frequencies.

For the study of non-stationary signals there is a relatively recent mathematical concept called the Wavelet Transform (WT), presented by Jean Morlet and Alex Grossman in 1984. The WT offers the possibility of studying signals longer time intervals for low frequencies and shorter time intervals for high frequencies. This can be considered as an advantage of WT about FT. Firstly, because it allows visualizing the performance of the signals in time and frequency simultaneously, and secondly because it allows the analysis of short transients. The WT takes a signal that is in the time domain and transforms it into the time and frequency domain. Although voltage, current, torque and speed signals are domain functions in time, in many cases, the most relevant information of them is in the frequency content, this is what motivates the use of the WT in the applications to signal analysis.

In this article, the review is made by the research work in which the WT has been put into practice to analyze electrical and mechanical signals of the IM. In section 2 some basic concepts of the WT are exposed, in section 3 some of the investigations in which the WT is used for the diagnosis of faults, control systems and electromagnetic disturbances are presented. Finally, in section 4, there are the conclusions that can lead future work of WT to the analysis of the IM performance.

2. Wavelet Transform

To talk about the WT, it is essential to mention the TF because, on the one hand, the definition of WT is based on the TF, and on the other hand, it is found that with the two transforms it is intended to represent a function in terms of other functions called bases. Once the WT is defined, the Multi Resolution Analysis (MRA) is defined, which is the theoretical foundation of the algorithm that allows the theory of the WT to put in practice.

2.1. Fourier's Transform

By the Fourier Theorem we have that the periodic functions can be decomposed into sinusoidal functions of different amplitudes and frequencies. This is what the equation represents (1).

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} A_n sen\,(\omega_n t) \quad + B_n cos\,(\omega_n\, t) \qquad Con\ \omega_n = \frac{2n\pi}{T} \quad n \in \mathbb{N} \tag{1}$$

Terms A_n and B_n are called the coefficients, W_n the frequency and the elements of the decomposition base are the functions *sen*($W_n t$) and *cos*($W_n t$).For non-periodic functions, the Fourier Transform (FT) is used, which assumes the infinite period and transforms a function f with a domain in time to a function F with a domain in the variable frequency w as shown in equation (2).

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \qquad \omega \in \mathbb{R} \tag{2}$$

2.2. *Some basic concepts about Wavelet transform*

It is said that a function ψ is square integrable (or finite energy) if it meets the inequality (3)

$$\int_{-\infty}^{\infty} |\psi(t)|^2 dt < \infty \tag{3}$$

The space of all square integrable functions with the norm defined in (4) is called $L^2(\mathbb{R})$.

$$\|\psi\|_{L^2} := \left(\int_{-\infty}^{\infty} \psi^2(t) dt\ \right)^{1/2} \tag{4}$$

Now, a square integrable function is a Wavelet (or Mother Wavelet) if it also satisfies the admissibility condition shown in (5. Where $\hat{\psi}(\omega)$ is the Fourier Transform of $\psi(\omega)$.

$$C_\psi := \int_{-\infty}^{\infty} \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega \quad < \infty \tag{5}$$

If in addition to admissibility, condition (6) is satisfied then the condition (7) will be satisfied the accordingly.

$$\int_{-\infty}^{\infty} \psi(t) dt \ < \infty \tag{6}$$

$$\int_{-\infty}^{\infty} \psi(t) dt \ = 0 \tag{7}$$

From a Mother Wavelet we define a family of functions that are compositions of translations and expansions of it, which are modeled as in equation (8). Where u indicates the translation and s indicates the dilation of ψ respectively

$$\psi_s^u(t) = \frac{1}{\sqrt{|s|}}\ \psi\left(\frac{t-u}{s}\right)\ u, s\ \in \mathbb{R} \tag{8}$$

If f is $L^2(\mathbb{R})$. function, its Continuous Wavelet Transform (TWC) is defined as:

$$TWC\ (u, s) = \int_{-\infty}^{\infty} f(t)\ \psi_s^u(t) dt \tag{9}$$

Since the *TWC* is defined for continuous $L^2(\mathbb{R})$ functions, usually for the purpose of implementing it computationally, a discrete version has been built. One way to discretize the parameters of scale and frequency is through an exponential sampling on the variables u and, to guarantee a better approximation with which the parameters u and discrete values can be redefined, are defined then: $u = 2^{-j} \in \mathbb{Z}$ y $s = k2^{-j}$ with $j, k \in \mathbb{Z}$. Therefore, the relationship described in (10) is obtained.

$$\psi_{j,k}(t) = 2^{\frac{j}{2}}\, \psi(2^j t - k) \tag{10}$$

With this selection of u and s the sampling in time is adjusted proportionally to the scale, on a larger scale, more distant points are taken, since global information is searched while at a smaller scale, details of the signal are searched, for this reason it is sampled in points less distant from each other.

Thus a function $\psi \in L^2(\mathbb{R})$ is Wavelet if the family of functions is an orthonormal basis fo $L^2(\mathbb{R})$.

In this case, the function f can be expressed as a combination of the elements of the base, obtaining that:

$$f(t) = \sum_{j,k} d_{j,k} 2^{\frac{j}{2}} \psi(2^j t - k) \ \ j, k \in \mathbb{Z} \tag{11}$$

Where the set of coefficients $d_{j,k}$ defined in ¡(11) are the Discrete Wavelet Transform of *f*.

$$\boldsymbol{d_{j,k} = \int_{-\infty}^{\infty} 2^{j/2} f(t) \psi(2^j t - k) dt} \tag{12}$$

2.3. *Multi Resolution Analysis (MRA)*

An MRA is increasing succession of closed subspaces $V_j, j \in \mathbb{Z}$ in $L^2(\mathbb{R})$ embedded,... $V_{-1} \subset V_0 \subset V_1 \subset V_2 \subset V_3 \ldots$, that satisfy the next five conditions:

- $\cup_j V_j$ Is dense in $L^2(\mathbb{R})$
- $\cap_j V_j = \{0\}$
- $f(t) \in V_j \Leftrightarrow f(2t) \in V_{j+1}$
- $f(t) \in V_0 \Leftrightarrow f(t-k) \in V_{j+1}$
- There is a function $\psi \in L^2(R)$ in which $\{\psi\,(t-k) \colon k \in Z\}$ constitute orthonormal base for V_0 space. Function ψ is the scale function.

Being the set W_j orthogonal compliment of each element V_j in V_{j+1} for each $j \in \mathbb{Z}$,is obtained, $V_j \cap W_j = \emptyset$, thus

$V_1 = V_0 \oplus W_1,\ V_2 = V_1 \oplus W_2, \ldots, V_j = V_{j-1} \oplus W_j$, as explained in [3]. And replacing v_j in V_{j+1}, for each $j \in \mathbb{Z}$, $V_j = V_0 \oplus W_1 \oplus W_2 \oplus W_{2\ldots} \oplus W_j$.

Now the set of linearly independent functions $\varphi_{j,k}$, which generate to V_j are named the scale functions, while those that generate W_j are the same Wavelets. Thus, the functions ψ show the "fine details" of the function, and the scales φ "make an approximation" of f. This way the function f can be approximated as a sum of these functions, as is shown in (13).

$$f(t) \sim \sum_k \sum_j c_{j,k} 2^{\frac{j}{2}} \varphi(2^j t - k) + d_{j,k} 2^{\frac{j}{2}} \psi(2^j t - k)$$

$$c_{j,k} = \int_{-\infty}^{\infty} f(t)\, \varphi_{j,k}(t) dt \quad d_{j,k} = \int_{-\infty}^{\infty} f(t)\, \psi_{j,k}(t) dt \tag{13}$$

Where numbers $C_{j,k}$ y $D_{j,k}$ are the coefficients of the decomposition and the number of times the detail functions are extracted, that is the value of J is the decomposition level.

3.Applications of Wavelet transform to induction motor analysis

Broad strokes it can be said that WT is used for several types of studies such as differentiating abnormal behavior of a signal, identifying discontinuities and points of drastic change, elimination of noise, compression of signal information and detection of self-similarities. In the case of electrical systems, applications from WT to IM have focused mainly on the diagnosis of faults, information analysis to feed the control systems and the identification of electromagnetic disturbances that affect the IM.

3.1. Failure Diagnosis

Failures that occur in an IM can be electrical or mechanical, and be originated by different reasons among which are the opening or shorting of one or more of a stator phase winding, incorrect connections in the stator windings, rotor field winding shorted, broken rotor bar or rotor end rings cracked, eccentricity, air gap irregularities, curved shaft, bearing and gearbox failures. The percentage of failures of the IM according to the information presented in [4] is distributed as follows Tread: 40%, Stator winding: 38%, Rotor: 10%, Other various: 12%.

There are techniques to detect and diagnose faults, those can be classified in the ones which do it with the motor in operation (on-line), and the other ones that are non-intrusive which do not require sensors. Generally, what is done to detect faults is a follow-up to the time-frequency evolutions of components related to faults during the transient of the starting current, these evolutions are identified, and also with a tool that can be TF or TTCF or WT, and the analysis of the results, the diagnosis of rotor or stator failure is concluded. There are several known methodologies among which are: The Motor Current Signature Analysis (MCSA) that is used to diagnose stator, short-circuit failure Motor Operated Valves (MOV`s) for the detection of broken rotor bars in valves operated by motors in the Nuclear energy industry, Electrical Signature Analysis (ESA), which takes into account both voltage and current signatures. For its identification of signatures, the TF, TFST have been used, but recently the WT is being applied.

For the detection and extraction of machines faults classification patterns investigations [5-13] are found, which from identifying current signatures characterize what type of failure is occurring in the IM. The broken bars of the rotor are one of the most difficult faults to detect, especially when the motor is powered by an inverter [14]. In [15] a methodology is proposed for an IM powered by an inverter during the start followed by a regime in steady state, and the ability to identify a single broken rotor bar, an eccentricity, and the combination of both faults is verified. The works exposed in [16-25] use the WT for this diagnosis of faults only of the rotor; while to detect the stator faults the works of [26-29] which DWT is applied to the stator current signal to calculate the energy associated with the Stator failure in the bandwidth of frequency where the total effects of the stator faults are located. And for the faults in the in-between iron which are less frequent, results with experimental validation are shown in [30-31].

In [32] comparisons of stator and rotor electrical faults are made through an IM model that uses Park's Instantaneous Space Fasor during the stator current analysis and the Transformer Fast Fourier (TFF), to identify the spectrum and the spectral density band of the Wavelet coefficients. One of the most frequent problems are those that occur in the bearings as reported by "---[33-38] where are proposed techniques to make a diagnosis based on the analysis of the wavelet coefficients. The bearing damage detection technique presented in "[35], for example, uses the Wavelet Packet energy coefficient analysis method to detect the Interior Rail Fault severity level (IRF) and an exterior Rail Fault (ORF).

In some cases the energy information associated with the faults is used as input to a neural network [39-44] which detects and locates it immediately. In other cases, in order to improve the results, the information obtained with WT has been combined with that extracted one using the Hilbert Transform [41], [45-46]. Wavelet with fuzzy logic has also been proposed to identify and quantify faults [47-48]. In [49] Wavelet with fuzzy logic has also been proposed to identify and quantify faults [50-51] as an input for Vector Support Machines (SVM) with which the conditions of the treads are classified [51].

Using MAR have been developed investigations as [52-56] which are focus on the application of WT to study voltage and current signals. Allowing visualizing good resolution in time and a poor resolution in frequency for high frequencies and a good resolution in frequency and lowing in time for low frequencies.

3.2. Control system

With the Fault Tolerant Control, it is intended to detect incipient failures in sensors and/or actuators, and quickly adapt the system for its proper functioning. In the review article [57], a large number of investigations are presented which have implemented WT for fault-tolerant control systems. In this article it is concluded, from the analysis of the researches reviewed, that Wavelet provides an effective method for the diagnosis of faults in comparison with other methods of signal processing. The Wavelet can correctly distinguish faults and thermal effects that make the IM parameters vary such as resistance and inductance.

In [58] it is proposed a speed controller for a vector control system without speed sensor, for this they apply the WT to the torque signal that is estimated through an observer. In [59] it is used to decompose the electromagnetic torque signal and optimize the inverter control strategy. Since the WT provides good information on Current Transients, and has shown good results in the applications that have been implemented, there are several proposals to implement WT in Control systems [59-67].

3.3. Electromagnetic disturbances

In the case of electromagnetic disturbances it has been observed that wavelet coefficients alone can be used as an efficient variable for the detection and identification of disturbances [68-71].

In [72] two algorithms based on WT which have detection and classification mechanisms are developed, to diagnose and detect different disturbances which happen in three-phase IM. Due to with WT is possible to decompose voltage wave forms and analyze the change in signal energy of three-phase instant power during the voltage dips, good results have been obtained in [73-75].

Research showed in [52] applies WT to torque and speed signal, to analyze voltage dips indirectly, studying the effect produced by the mechanical variable. It is affirmed that mechanical variables contain information about the sort of three-phase tension gap produced in the stator. The results of the decomposition with TW of the disturbed signals of the torque and speed of the motor shaft are also presented, when subjecting it to the different types of voltage dips according to the ABC classification.

Research that present criteria for deciding which Mother Wavelet and from which order it must be used in different problems that require frequency spectrum analysis are not found. Although some authors affirm that Mother Wavelet with Daubechies filters for energy quality analysis is quite trustworthy [54].

Although, there are no methods to select the right Wavelet for specific signal treatment, it is recognized the existence of the right Daubechies to apply in discreet signal analysis, Coiflet and Symmlet which being similar to Daubechies have symmetry. Biorthonormals is a family that presents lineal phase property what is really useful for image rebuilding, in this case it is necessary to use a Mother Wavelet to decompose and other to rebuild. In [76] t is proposed a method that selects the right Wavelet for transient electrical signals.

Some research which show the use of Wavelet but don't correspond with the groups previously shown are for example the one reported in [77], which is a proposal of a non-intrusive in-situ efficiency estimation method and tool for IM without any shaft or rotation sensor. There also show some works which are engaged in characterize electric systems waves [78-79]. In [80] a detailed comparison is made between the two main groups of transformations that are used in the transient analysis: discrete and continuous.

4. Conclusions

WT has been applied in IM signals analysis with important results: the most frequent of those enforcements are the ones related with motor failure detection, control systems and electromagnetic perturbations identification which are shown in the power supply.

Furthermore, about failure detection, the results show that energy coefficients from Wavelet are not only sensitive to detect failures but also to detect the severity of the failure. In the cases in which WT data is mixed with other algorithms, strong results in accuracy and calculation time are generated.

On the research analyzed it is not specified if results obtained apply to high, medium or low power motors, and only in punctual cases it is mentioned the load and speed conditions of operation for which experimental tests were made.

There are not important advances to choose the most appropriate Wavelets for and specific sort of problem.

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