International Journal of the Physical Sciences Vol. 6(3), pp. 358-376, 4 February, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS10.632

Review

Wavelet fault diagnosis and tolerant of induction motor: A review

Khalaf Salloum Gaeid* and Hew Wooi Ping

Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.

Accepted 12 January, 2011

This paper presents a review of the researches done on fault tolerant control types, methods, main objectives of the fault tolerant control and fault diagnosis of induction motor faults that used the wavelet transform. Wavelet transform from the fault diagnosis point of view, is a summary of the wavelet types (continuous and discrete), machine faults, diagnosis methods and their validation, respectively. Types of software, generality of codes, one dimensional and two dimensional DWT and frequency characteristics components of healthy and faulty induction motor are given. Finally, stator short winding and open winding are taken as a case study to show the effectiveness of the wavelet techniques for fault diagnosis.

Key words: Wavelet, induction motor, fault diagnosis, fast Fourier transform, fault indicator, fault tolerant control.

INTRODUCTION

Induction motor is crucial in industries for many reasons, such as simple construction, low maintenance requirement, rigid and high reliability like compressors, pumps and fans. Since the induction motor current contains harmonics that are used as fault indication of many faults, Figure 1. shows the induction motor faults percentages, squirrel cage motor are mostly important due to the fact that they can work under fault conditions without any visible fault seen until the fault becomes high (Khalaf et al., 2010). However, this fault has a relative cheapness and high reliability (Bodkhe and Aware, 2009). Many different techniques used for the detection of faults concentrate on the stator fault due to noninvasive properties. The mathematical equations used to separate a given continuous-time signal into several scale components is called wavelet. The wavelet techniques are new in the field of fault diagnosis due to its ability to extract information in both time and frequency domain as well as it provides a sensitive means to the diagnosis of faults if compared to other signal processing methods like Fourier. A good review was presented for the diagnosis of machines using a condition-based maintenance approach by Andrew et al. (2006). The fault diagnosis has two main levels: (1) It comprises a traditional control level and (2) it contains a knowledge based fault diagnosis.

Fault diagnosis techniques contain feature extraction module (wavelet), feature cluster module and fault decision module (1). The negative sequence current and impedance are chosen as good fault indicators, while Park's vector and the motor current signature analysis (MCSA) are used to diagnose the stator short circuit fault. One of the most important analysis tools in both frequency and time domain is the wavelet. The multi resolution analysis and good time localization makes the wavelet very attractive for the researchers in fault diagnosis. Signal processing techniques, like FFT, are based on the following assumptions: that the constant of the stator fundamental frequency, load and motor speed is sufficient so it cannot be used with nonlinear systems. SIEBER LS71 induction motor parameters are used in the modeling of induction motor as it can be seen in Table 1.

This paper is organized as follows. First, it presents the

*Corresponding author. E-mail: khalaf_gaeid@yahoo.com.

Table 1. SIEBER LS71 induction motor parameters.

Motor specification	Unit	Value
Power	kw	0.5
Current	Ampere	1.7
Voltage (delta)	Volt	230
Rated speed	RPM	2800
Poles		2
Moment of inertia	$Kg.m^2$	3.5e-4
R_s	ohm	24.6
R_r	ohm	16.1
L_s	Henry	40e-3
L_r	Henry	40e-3

fault tolerant control of induction motor and then the wavelet of induction motor fault diagnosis. Lastly, a case study is presented to investigate the effectiveness of wavelet in the field fault diagnosis. Rong-Jong and Jia-Ming (2002) proposed a new intelligent control of induction motor using neural network with wavelet to get a good tracking performance. Campos-Delgado et al. (2008) presented a good review on the fault tolerant control in both induction motor and DC motor. They studied the common fault scenarios, diagnosis strategies, artificial intelligence and fault accommodation schemes that were suggested. Sang-Hyuk et al. (2006) presented the stator current fault detection using Fourier and wavelet with intelligent control to detect and separate the faulted data.

Fault tolerant control

Many efforts in the control community have been recently devoted to study "fault-tolerant" control (FTC) systems, namely Ron et al. (1997) who present fault-tolerant control systems. They presented good details for the types of fault tolerant control, its areas, architecture and control systems, which enable them to detect the incipient faults in sensors and/or actuators on the one hand and on the other, to promptly adapt the control law in such a way as to preserve pre-specified performances in terms of the quality of production, safety, etc. The fault tolerant control consists of two steps:

(1) Fault diagnosis.
(2) Re-design controller.

Currently, FTC in most of the real industrial systems is realized by hardware redundancy. For example, the majority-voting scheme is used with redundant sensors to cope with sensor faults. However, due to the two main limitations of the hardware redundancy (high cost and occupying more space), solutions using analytical redundancy have been investigated over the last two decades. There are generally two different approaches using analytical redundancy:

(1) Passive approaches (classical control)
(2) Active approaches (adaptive control).

Recently, an elegant design method of the passive approach was proposed, in which the linear matrix inequality (LMI) method was used to synthesize the reliable controller.
The disadvantages of the passive approach are:

(a) The method is based on an accurate linear state space model and therefore it is not capable of controlling a non-linear process for which an accurate analytical model is usually unavailable.
(b) For the fact that the passive approaches consider fault tolerance in only the stage of controller design and without taking adaptation when faults occur, the amplitude of the faults that can be tolerable is usually small and cannot meet the requirements in practice.

There are many methods that deal with the active fault tolerant control such as linearization feedback, linear quadrature method, Pseudo inverse method, Eigen structure assignment method, neural network, control law rescheduling, model predictive control MPC, H_∞, norm optimization and 4 parameter controllers. The main disadvantage of their designs is that they consider large fault effects which do not challenge the robustness problem. A consideration of smaller or incipient (hard to detect) faults would have given a more realistic and challenging robustness problem to be solved. The remote diagnosis is another type used with the fault tolerant control. As such, the FTC can be classified also due to the fact that:

(i) The off board component has (nearly) unlimited computing power, but has to cope with the limited and possibly biased measurement data.
(ii) The on board component has to work with the restricted computing power and memory size which limits the algorithm complexity of the task to be performed.

Xiaodong (2002), in his Ph.D thesis, presented a novel isolation scheme with its robustness and sensitivity properties using adaptive thresholds in the residue evaluation stage in the three tank system, a rigid link robotic manipulator and the Van der Pol oscillator system. Haider et al. (2008) proposed a fault tolerant control design that consists of two parts: a nominal performance controller and a fault detection element to provide fault compensating signals to the feedback loop. The nominal controller can have any given structure that satisfies the performance specification, and so the detection element will operate in parallelism with the system until a fault is detected.

Fault tolerant operations of soft starters and adjustable-speed drives (ASDs) when experiencing power switch open-circuit or short-circuit faults are presented in Chia-Chou (2007). Jean-Etienne et al. (2007) presented a method for designing switching controls and analyzing achievable performance for motor drives to maintain the system operation. A collection of results towards a unified framework for fault tolerant control in the distributed control systems are given in Andrea (2003). Amr et al. (2006) present a fault tolerant strategy for the problem of loss of one phase in a field oriented controlled three phase induction motor, in which the proposed solution, rather than previously suggested solutions, is a control strategy in the single phase mode of operation of the induction motor. Same authors describe a novel strategy for restarting the three phase induction motor in a voltage fed field oriented drive operating in the single phase mode after the loss of one of the inverter phases (Amr et al., 2007).

Sejir et al. (2006) presented an original strategy of fault tolerant operation in the case of the doubly fed induction machine (DFIM), whereas Jacobina et al. (2004) investigated the voltage and current control of a five-phase induction motor drive under fault conditions. Mendes et al. (2003) exploit the advantages and the inconveniences of using remedial operating strategies under different control techniques, such as the field oriented control and the direct torque control. Global results, concerning the analysis of some key parameters like efficiency and motor line currents harmonic distortion, are presented among others. Nademi et al. (2008) considered the problem of designing a fault tolerant system for the IPMS motor drive subject and the current sensor fault. To achieve this goal, two control strategies are considered.

The first is based on a field oriented control and a developed adaptive back stepping observer which are simultaneously used in a fault-free case, while the second approach concerns itself with a fault tolerant strategy that is based on observer for faulty conditions. However, Halim et al. (2008) proposed an on-line sliding mode control allocation scheme for fault tolerant control. The model-based fault detection and isolation schemes used to reduce or eliminate the effect of unknown disturbances on the multi input and multi output induction motor, and the effectiveness level of the actuators and sensors faults was studied by Khalaf and Hew (2010).

Anjali et al. (2008) presented a novel intelligent nonlinear state estimation strategy, which keeps the root causes of the plant model mismatch diagnosed by isolating the subset of active faults (abrupt changes in parameters/disturbances, biases in sensors/actuators, actuator/sensor failures) and auto-corrects the model on-line so as to accommodate the isolated faults/failures. Matthew et al. (2004) considered a control system design for a rotor magnetic bearing system that integrates a number of fault-tolerant control methods, whereas Wai-Chuen and Li (2003) presented a plug-in robust compensator for speed and position control enhancement of an indirect-field-oriented-control induction machine drive.

In a study by Vukosavic et al. (2005), a vector control algorithm, based on indirect rotor flux orientation, was briefly described, with special attention paid to the current control issue, from the point of view of the minimum number of current controllers for the six phase induction motor. The IFOC can transform the induction motor from a nonlinear into a linear system, but with many assumptions. It is well known that the output response is sensitive to the plant parameters variations such as the rotor resistance. In Youmin and Jin (2008), a bibliographical review on the reconfigurable (active) fault-tolerant control systems (FTCS) was presented. The existing approaches to fault detection and diagnosis (FDD) and fault-tolerant control (FTC) in a general framework of the active fault-tolerant control systems (AFTCS) are considered and classified according to different criteria, such as:

(1) Design methodologies
(2) Applications as seen in Figure 2.

Hui-Wei et al. (2008) presented an adaptive fault tolerant control (FTC) of nonlinearly parameterized systems with uncontrollable linearization. The progress was made due to the development of a novel feedback design technique called adding a power integrator, which was motivated by homogeneous feedback stabilization and was proposed initially for global stabilization of nonlinear systems with uncontrollable linearization. Fekih et al. (2009) presented a new strategy for the fault tolerant control of aircraft systems, while Romero et al. (2009) proposed the uses of multisensor switching control strategy for fault tolerant direct torque and flux control of the induction motor.

Ghoshal et al. (2009) presented the analytical redundancy relation (ARR) based approach for fault detection and isolation (FDI) with application to the hydraulic and thermo fluid process using Bond graph to model the FDI.

Stoyan (2004) introduced, in his PhD thesis, the main methods in fault tolerant control.

Typically, an active FTCS consists of three parts:

(1) A robust reconfigurable controller
(2) AN FDD scheme with high sensitivity to faults and robustness to model uncertainties and external disturbances, (including residual generation, residual evaluation and threshold determination), and
(3) A reconfiguration mechanism which can organize the reconfigured controller in such a way that the pre fault system performance can be recovered to the maximum extent.

Nonetheless, a control law reconfiguration mechanism is shown in Figure 3.

According to the depth of the information used by the physical process, the approaches to the problem of failure detection and isolation fall into two major groups:

Figure 1. Induction motors faults percentages.

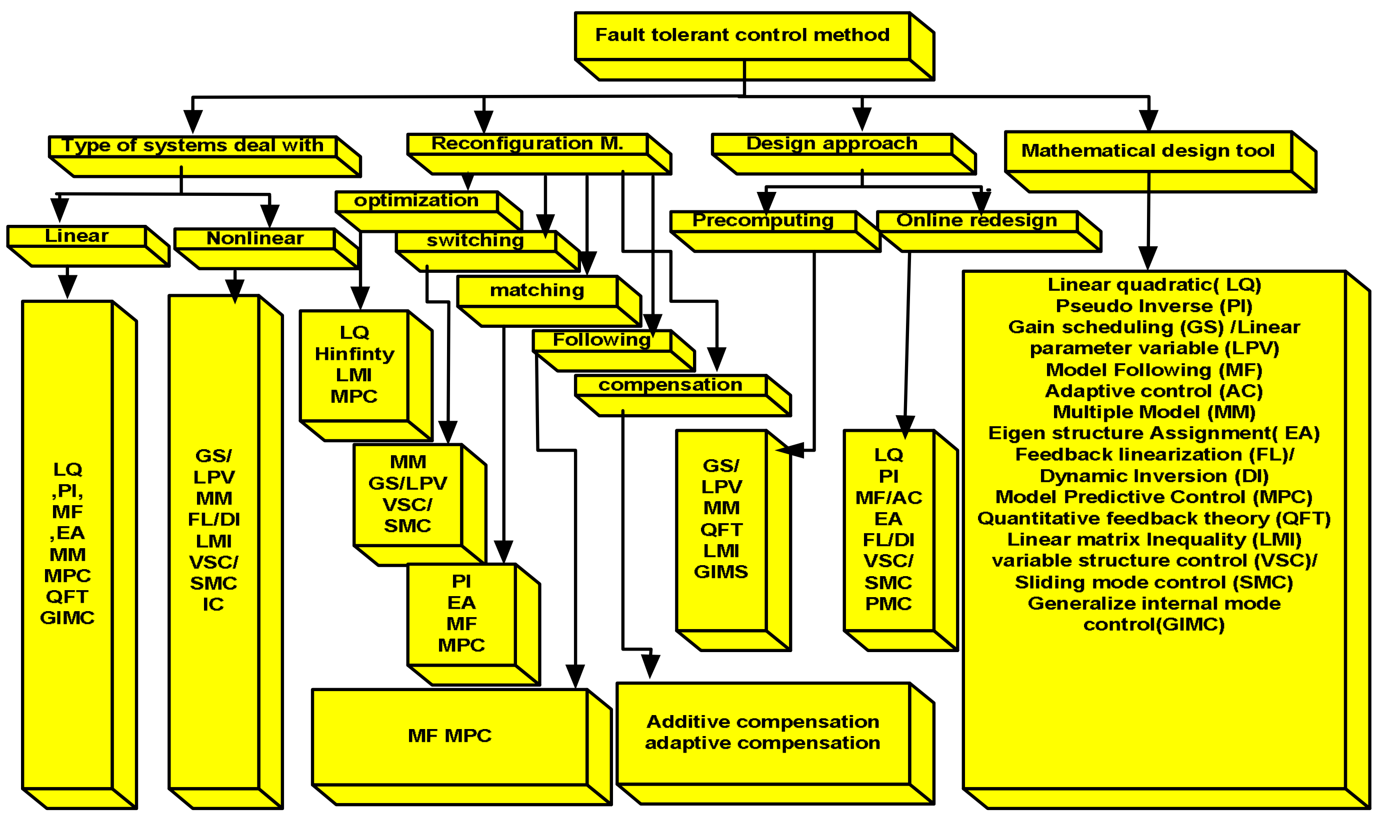

Figure 2. Active fault tolerant control methods.

(1) Methods that do not make use of the mathematical model of plant dynamics, or model-free FDI.
(2) Methods that do make use of the quantitative plant model, or model-based FDI.

The existing FDI approaches can be generally classified into two categories:
(a) Model based schemes and
(b) Data-based (model-free) schemes.

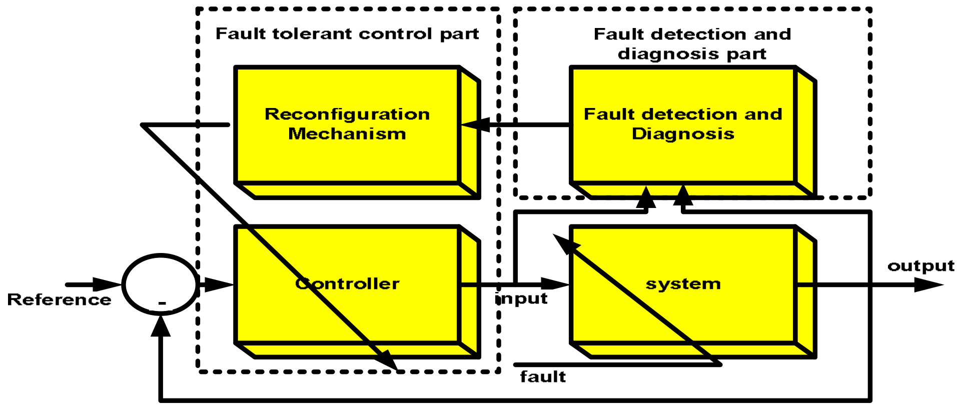

Figure 3. Main component of the fault tolerant control.

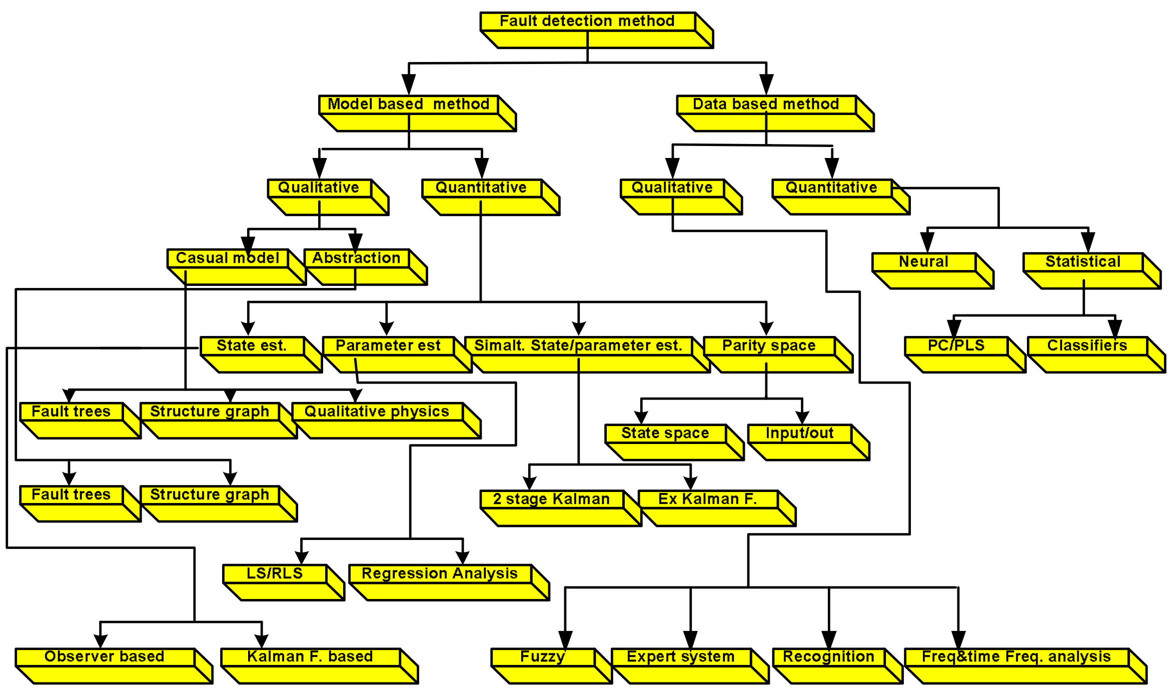

Figure 4. Methods of fault detection and isolation part of FTCS.

These two schemes can further be classified as quantitative and qualitative approaches as shown in Figure 4.

TRANSFORMATION TYPES OF WAVELET

Wavelet transformation contains many kinds, but in this paper, the most important among them will be introduced, such as:

(1) Discrete wavelet transformation
(2) Continuous wavelet transformation
(3) Wavelet packet decomposition transformation

There are more than ten transformation types of wavelet, but the ones mentioned are the most famous according to their usage in the fault detection and diagnosis of induction motors. The wavelet is divided into two main groups: the discrete wavelet transform and the continuous wavelet transform, which is divided into two subgroups namely the real wavelet as can be seen in Table 2 and the complex wavelet as can be seen in Table 3. The CWT can be written as follows:

$$\omega(m,n) = \int_{-\infty}^{\infty} f(t)\psi^{*}_{m,n}(t)\,dt \qquad (1)$$

Table 2. Continuous real wavelet transforms.

Beta wavelet	$\psi_{beta}(t/\alpha,\beta)=(-1)dp(t/\alpha,\beta)/dt$
Hermitian wavelet	$\psi_n(t)=(2n)^{-n/2}C_nH_n(t/\sqrt{2})e^{(-1/2n)t^2}$
Mex.hat wavelet	$\psi(t)=(2/\sqrt{3}\sigma\pi^{1/4})(1-t^2/\sigma^2)e^{(-t^2/2\sigma^2)}$
Shannon wavelet	$\psi(t)=2\sin c(2t)-\sin c(t)$
Beta wavelet	$\psi_{beta}(t/\alpha,\beta)=(-1)dp(t/\alpha,\beta)/dt$
Hermitian wavelet	$\psi_n(t)=(2n)^{-n/2}C_nH_n(t/\sqrt{2})e^{(-1/2n)t^2}$
Mex.hat wavelet	$\psi(t)=(2/\sqrt{3}\sigma\pi^{1/4})(1-t^2/\sigma^2)e^{(-t^2/2\sigma^2)}$
Shannon wavelet	$\psi(t)=2\sin c(2t)-\sin c(t)$

Table 3. Continuous complex wavelet.

Mexican hat wavelet	$\psi(t)=\frac{2}{\sqrt{3}}\pi^{-0.25}\left(\sqrt{\pi}(-t^2)\,e^{-0.5t^2} - -\sqrt{2}\,i\,t\sqrt{\pi}erf\left(\frac{i}{\sqrt{2}}t\right)\left(1-t^2\right)e^{-0.5t^2}\right)$
Morlet wavelet	$\psi(t)=(C\pi^{-(1/4)})e^{-1/2t^2}(e^{it}-k)$
Shannon wavelet	$\psi(t)=\sin c(t)e^{-j\pi t}$
Modified Morlet wavelet	$\psi(t)=C_\psi\cos(\omega_o t)\sec h(t)$

*denotes the complex conjugate, where *f(t)* is the wave form signal and ψ(t) is a wavelet.

$$\psi_{m,n}(t)=2^{-1/2}\psi(2^{-m}t-n) \qquad (2)$$

m and *n* controlling are the wavelet dilation and translation, respectively, used to transform the original signal into a new signal with smaller scales according to high frequency components. This relation is valid for the orthogonal basis of wavelet transform (a = 2 and b = 1). In the following continuous wavelet transform, *a* is the scale parameter, while *b* is the time parameter.

$$\omega_{a,b}(t)=|a|^{-1/2}\,\psi(\frac{t-b}{a}) \qquad (3)$$

The wavelet families are divided into discrete and continuous wavelet; though the DW will be written first with their mathematical relationship (Table 4). In digital computers, the discrete wavelet transform is a good choice, while the mother wavelet is scaled in the power of 2 as in Salehi and Jalilian (2010). The continuous wavelet transform (CWT) was developed as an alternative approach to overcome its resolution problem as it is shown in Table 2 (Lorand, 2005). There are two important properties in the wavelet; the first is the admissibility and the second is the regularity conditions which can be illustrated as in the following equations:

$$\int\frac{|\psi(\omega)|^2}{|\omega|}d\omega<+\infty \qquad (4)$$

Table 4. Discrete wavelet transforms.

Coiflet discrete wavelet	$B_k = (-1)^k C_{N-1-k}$
Cohen Daubechies wavelet	$B_k = (-1)^k C_{N-1-k}$
Daubechies wavelet	$B_k = (-1)^k C_{N-1-k}$
Binomial-quadrature mirror filter (QMF)	$h(n) = \sum_{r=0}^{N-2/2} \theta_r X_r(n)$
Haar wavelet	$\psi_{n,k}(t) = \psi(2^n t - k)$
Mathieu wavelet	$H_v(\omega) = -e^{-jv\omega/2} \frac{ce_v(\omega/2, q)}{ce_v(0, q)}$
Legendre wavelet	$H_v(\omega) = 1/\sqrt{2} \sum_{k \in Z} h^v e^{-j\omega k}$

Table 5. Induction motor fault diagnosis methods validity.

Faults method	Bearing	Stator winding	Air gap eccentricity	External (sensors)
MCSA	Ok	Partial	Ok	Not
Vibration analysis	Ok	Not	Ok	Not
Axial flux	Not	Partial	Ok	Not
Partial discharge	Not	Ok	Not	Not
M.B FDD	Not sure	Ok	Not sure	Not

where ψ(ω) is the Fourier transform of the wavelet function ψ(t), used to investigate the signals and then to reconstruct it without losing any information, which means it would be equal to zero according to the following equation:

$$|\psi(\omega)|^2 = 1 \quad (5)$$

Another important property of the wavelet is:

$$\int \psi(\omega) = 0 \quad (6)$$

Signal processing techniques of induction motor faults

In this context, the main faults in the induction motor and their validity (Table 5) will be taken into consideration, and a summary of the fault diagnosis methods properties (Table 6) will be written down.

Air gap eccentricity

The mechanical faults that happened due to many reasons such as machine manufacturing, assembly unbalance load, bent shaft and bearing wear (Tsoumas et al., 2005) used the wavelet of current space vector to detect the broken rotor bar and air gap eccentricity faults:

$$f_{ecc} = f_s\left(1 \pm k.\frac{1-s}{p}\right) \quad (7)$$

$$f_{brk} = f_s(1 \pm 2ks) \quad (8)$$

Cusido et al. (2007, 2008) presented the wavelet detection using MCSA method because it needed not more than a single line current, and according to the position of the side band frequencies around 50 Hz, they classified the faults due to the following equations:

$$f_{ecc} = f_1\left[1 \pm m\left(\frac{1-s}{p}\right)\right] \quad (9)$$

Table 6. Summary of the fault diagnosis methods properties (Khalaf et al., 2010).

Techniques	Required measurement	Application	Advantages	Drawbacks
Motor current signature Analysis(MCSA)	One stator current	1.Rotor broken bar 2.Stator winding turn fault 3.Air gap eccentricity	1.Low cost 2.Non invasive	1.Frequencies' vary from motor to other 2.Lilted to some states
Complex park vector (CPV)	Two stator currents	1.Rotor broken bar 2.Stator winding turn fault 3.Air gap eccentricity	1.Non invasive 2.Simple	Mismatches faults
Axial flow (AF)	Axial flux	1.Rotor broken bar 2.Stator winding turn fault 3.Air gap eccentricity	1.Low cost	Non invasive
Torque harmonics analysis (THA)	Two stator currents and voltages	1.Rotor broken bar 2.Stator winding turn fault 3.Mechanical faults in load	1.Mechanical fault detection 2.Non invasive	Not effective in short circuit. faults
Impedances of inverse sequence (IIS)	Two stator currents and voltages	Stator winding turn fault	1.Incipient faults detection 2.Non invasive	Required great measurement precision
ANN	Two stator currents and voltages	Stator winding turn fault	1.Incipient faults detection 2.Non invasive 3.Easily to adapt to each motor	1.Required training period 2.Not effective in the motors changes states

$$f_{ecc} = f_1\left[\frac{n}{p}(1-s) \pm k\right] \tag{10}$$

$$f_{brb} = f_1\left[m\left(\frac{1-s}{p/2}\right) \pm s\right] \tag{11}$$

$$f_{airgap} = \left| f_1 \pm m f_{i,o} \right| \tag{12}$$

Hamidi et al. (2004) presented the detection of a mixed eccentricity fault using WPD, which was done by a modified winding function. Antonino et al. (2006) presented the detection and diagnosis of mixed eccentricities and rotor asymmetries with different sizes and conditions as well as effective oscillations due to the load torque or voltage that were studied individually. Antonino et al. (2009) presented many cases for fault diagnosis (mixed eccentricity, broken rotor, inter-turn and inter-coil stator short-circuits) using DWT at start up current of induction machines according to the stator parallel branches. Antonino et al. (2005) presented the detection of mixed eccentricities fault in the induction motor using Hilbert Huang Transform with DWT. Zhongming et al. (2000) used WPD to detect both air gap eccentricity and broken rotor bar after giving a brief detail about the wavelet and feature extraction.

Gear box and bearing faults

The mechanical frequencies needed to investigate

Table 7. Induction motor frequency characteristics formulas.

Air gap eccentricity fault	$fecc = fs\,(1 \pm k.(1-s)/p)$
Broken bar	$f_{brk} = f_s(1 \pm 2ks)$ & f_{brk} = k/p(1-s)±s)fs, with k/ k p=1,3,5
Healthy machine harmonic	$f_{psh} = \left[k\frac{R}{p}(1-s) \pm v\right] f_{nst}$
Inter turns short circuit of stator winding	$f_{st1} = (3-2s)f$ & $f_{st2} = (5-4s)$
Fault frequency component of bearing inner ring	$f_{bri} = \frac{N}{2} f_r(1 + \frac{D_b}{D_c}$Cos (α)

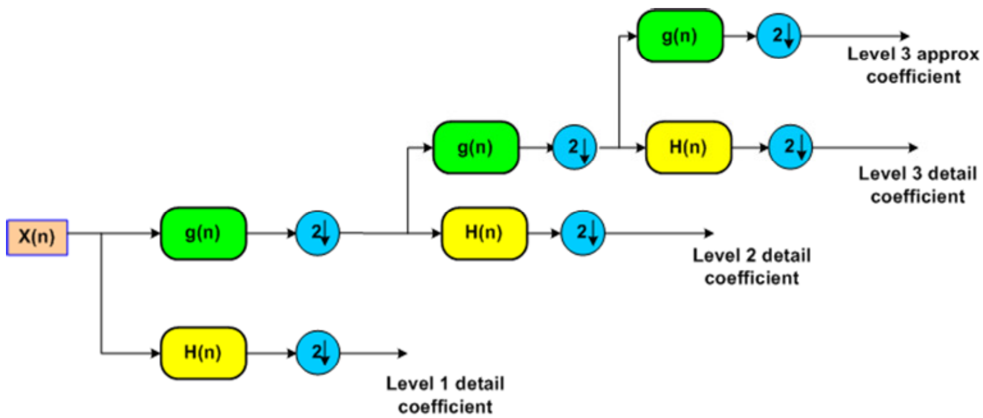

Figure 5. Wavelet decomposition.

the mechanical fault such as gear box are shown in Table 7.

Yixiang et al. (2010) used the lean model to assess the machine performance via DWT for the vibration and bearing induction motor faults. Bin and Paghda (2008) used the wavelet to detect the broken rotor bar, eccentricity and bearing due to current, voltage and instantaneous power, while the signals to noise ratio of the spectral components were examined under varying load condition of the single phase in the active cycle. Rafiee et al. (2010) presented a study of how the mother wavelet is chosen among 324 using four statistical features to decide the db44, which is better in their application. Jafar and Javad (2007) used Meyer wavelet in the WP structure to detect the bearing defect using SCA with energy comparison as the fault index. Jawad and Mansour (2009) presented a review for most important indexes in the different types of eccentricities faults in the induction motors as well as the consequences and effects.

Qiao et al. (2007) presented fault diagnosis of rolling bearings, and the testing results show that the support vector machines can separate different fault conditions and identify the severity of incipient faults. In addition, it gives better classification performance compared to the single SVMs. Serhat et al. (2008) presented feature extraction using wavelet technique to detect the bearing fault of 5HP (Serhat and Emine, 2003). Singh et al. (2009) presented and detected the bearing fault of the induction motor to treat and analyze the following signals (three line to line voltages, three currents, two vibration signals, four temperatures and one speed signal) obtained from monitoring using wavelet transform. Chinmaya and Mohanty (2006) studied a multi-stage transmission gearbox in order to use the MCSA instead of the conventional vibration monitoring with DWT and FFT to investigate the sideband frequencies.

Abbasion et al. (2007) introduced the support vector machine (SVM) as a classifier to compute optimum wavelet decomposition and the diagnostic rolling of the element bearings fault in the induction motor. Cusido et al. (2006) presented a new method, which combines wavelet and power spectral density techniques to detect the bearing defect using the power detail density (PDD) as a fault factor as can be seen in Figure 5. Rui et al. (2010) used wavelet for the vibration signal based mechanical equipment fault diagnosis, while the algorithm were implemented using the WEKA algorithms (Waikato Environment for Knowledge Analysis). Kaptan et al. (2007) presented the application of MCSA using WPD to detect bearing faults in adjustable speed drives. Temperature monitoring, which is the mean, measuring the component and operational temperatures, is another trend that can be used for the diagnosis of induction motor, particularly in the gears.

Stator faults result of opening or shorting the stator coil or phase winding

The mechanical frequency needed to investigate the electrical faults is shown in Table 7. Tong and Jin (2005) presented an Eigen vector as a fault indicator of the stator inter turn short circuit as follows:

$$T = \left[\frac{E_0}{E}, \frac{E_1}{E}, \ldots, \frac{E_{2M-1}}{E} \right] \quad (13)$$

T, E is the Eigen vector and energy Eigen value respectively, and it contains the necessary information of the electromagnetic torque signal as in Equation 14:

$$E = \sum_{j=0}^{2^M - 1} \left(abs(E)^2 \right)^{0.5} \quad (14)$$

Mohammed et al. (2006, 2007) presented, in two papers, the FE modeling of the induction motor internal faults and solved the equation by a time stepping approach of the broken bar and stator shorted turns using db10 wavelet for both sinusoidal and non-sinusoidal, respectively. Software diagnosis of short inter turn and open circuit of the stator winding as an incipient fault was done by Ponci et al. (2007) to avoid hardware cost and difficulty using wavelet decomposition for different stator resistance (*Rs*=0.001, 0.1, 0.7, 1, 4, 8) Ω. Table 8 gives the wavelet software, types and generality.

MCSA are used to detect faults with wavelet, while the stator teeth harmonic variation used dq0 components instead of *Iabc* as in Cusido et al. (2006). Gang et al. (2008) employed the Bayesian belief fusion and the multi agent fusion as a classifier tool to detect different faulty collected data using the signal processing techniques for smoothing and then using DWT to decompose the signals into different ranges of frequency as shown in Figure 6. Riera et al. (2009) presented a detection and diagnosis of rotor asymmetries in induction motor. Based on the analysis of the stator startup current, the authors extracted the harmonic component introduced by this fault at the left sideband component from the stator startup current, while the digital low-pass filtering (DLPF) and (DWT) were used by this technique. Combastel et al. (2002) presented a comparison between model-based and signal-based approaches in fault detection of the induction motor. The electrical variables were described according to the park transformation model, while the broken rotor and stator winding failures were investigated. In addition, the parameter variations due to heating were considered. Radhika et al. (2010) presented fault diagnostics of the induction motor using MCSA with WT extracted features that are classified using support vector machine (SVM). Chao-Ming and Loparo (1998) presented a fault detector in the vector controlled induction motor to compute a ”fault index” for the faults of stator winding.

Shorted rotor field winding

Khan et al. (2006) present two DWT to detect and classify the faults that occur in the rotor of the induction motor. The continuous wave let is a part of the wavelet used to detect the faults, especially when the overlapping between the frequency supply signal and the adjacent signal cannot be recognized. Six accelerometers used to measure the vibration data of 5 kW put in independent places around the motor detect the bearing damage (Ayaz et al., 2006).

Saleh et al. (2005) presented a new technique for detecting and diagnosing faults in both stator and rotor windings using wound rotor induction motor. This technique is based on a (WT MRA). Cusido et al. (2007) presented both continuous and discrete wavelet to detect many mechanical and electrical induction motor faults using MCSA.

Broken rotor bar and crack end ring

The rotor broken bar frequency is an asymmetry condition that is shown in Table 7.

Zhang et al. (2007) used the EMD which deals with nonlinear systems to detect the broken rotor bar using WDT. Cao et al. (2001) used the multi resolution wavelet analysis method to detect the broken rotor bars according to the analysis of stator current. According to this work, the signal was first filtered and then differentiated. Afterwards, it was entered into the wavelet (Daubechies with 5 levels). Faiz et al. (2007) presented a novel criterion to detect the broken rotor bar using TSFE to model the broken bar faults in induction motor. The criterion function used to detect the fault is:

$$criterion \;\; funct = \frac{avg\,.of \;\; fluctuatio \;\; n \;\; for\,(abs\,(D4))}{mean \;\; current} \quad (15)$$

Cunxiang et al. (2007) presented a novel method to detect the rotor broken bar using ridge wavelet. In this paper, only one phase of the stator current, enough to extract the characteristics frequency component of the broken bar, is shown in Table 7. Pons-Llinares et al. (2009) presented a new method to detect the broken bar in the transient region using TMCSA via frequency B-Splines. However, the mother wavelet equation that they used was:

$$\psi(t) = C_{m,\,nf} \, \sin c^m \left(\frac{fbt}{m} \right) e^{j2\pi fct} \quad (16)$$

Table 8. Wavelet software (Niklas, 2003).

Type of software	Generality	Type of code	1D and 2D DWT and SWT compression (C) and de-noising (D)
Lifting notebook mathematical	Specialized	Research	The main feature of this software is automated factorization in lifting scheme
Wavelet explorer mathematica	Very general	Commercial	1D and 2D compression and de noising
Wavelet Toolbox MATLAB	Very general	Commercial	Global, level-dependent and/or interval/orientation dependent hard or (for D only) soft thresholding strategies: Noise (D): Scaled white, unscaled white or colored. Donoho-Johnstone methods (D): 1D and 2D: Fixed-form 1D: Heursure, rigsure, minimax. Empirical methods: Balance sparsity-norm (C) or (for 2D C and D) square root of this threshold. Birg´e-Massart methods: Penalized high /medium/low (D) and (for C and non global thresholds) scarce high/medium/low. C Remove near 0.
Wave Lab MATLAB	Very general	Research	High-level commands for the following 1D DWT de noising methods under the assumption of white Gaussian noise of variance 1: global threshold: Visually best (soft or hard) threshold (p2 log n). Minimax hard threshold. Level- dependent thresholds: Hard SURE threshold. Soft modified SURE threshold. Visually best soft threshold with level- dependent noise level estimation.
Rice W.T MATLAB and C	General	Research	Soft or hard threshold Variance estimator: MAD (mean absolute deviation) or STD (classical numerical std estimate).
TF Toolbox MATLAB	General	Research	Used widely in signal processing. filters, recognitions, detections
Wavekit MATLAB and C	General	Tutorial	Good for tutorial, manual and demonstration some instruction can be written in C but with care.
Wave++ C++	Specialized	Research	Used for both DWT& WP but need good knowledge in C++
WZICwP C++	Specialized	Research	Used for image compression in C++
WaveThresh3 R(window and Linux)	General	Research	used as statistics approach in wavelet techniques

where m = 2.

Pineda-Sanchez et al. (2009) used the fractional Fourier transform as a spectral analysis tool with the TMCSA to detect the rotor broken bar (Figure 7). Eren et al. (2002, 2007) presented the bearing fault defects of the induction motor WPT decomposition of 1 Hp induction motor stator current through the test of RMS for both healthy

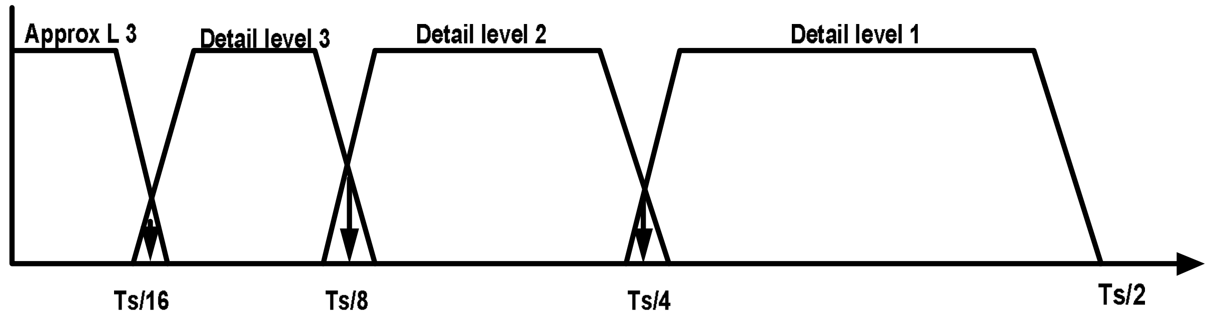

Figure 6. Frequency ranges for details and final approximation.

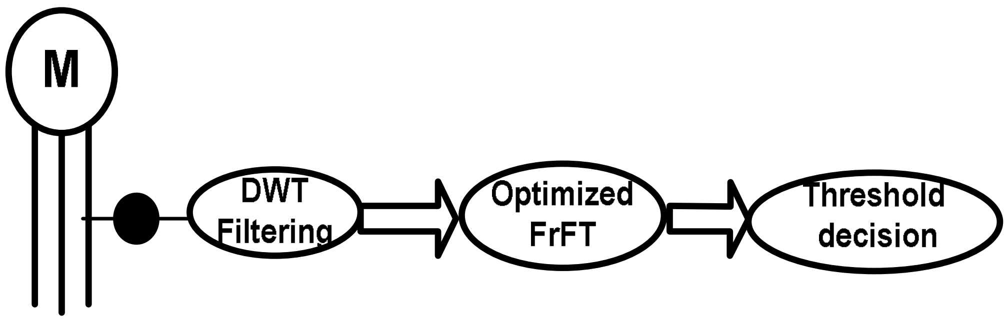

Figure 7. The TMCSA diagnosis system.

and faulty bearings.

The signal mean square of the discrete wavelet function computation used to detect the statues of the broken rotor bar of induction motor, using either healthy or faulty FPGA, was introduced in (Ordaz et al., 2008) their novelty weighting function as shown in (17).

$$\omega f_{brb} = \sum_{k_1}^{k_2} [\omega c_{brb} (j.k)]^2 \qquad (17)$$

Abbas et al. (2001) presented a novel approach that will be used to detect the broken bar fault in squirrel cage induction motor. Two 3 hp induction motor with cast aluminum rotor bars are employed for this experiment. Cabal-Yepez et al. (2009) used FPGA to detect many fault in squirrel cage, such as unbalance, faulty bearing and broken bars using parallel combination of fused FFT and wavelet. Antonino et al. (2009) presented new techniques for detection of the broken bar using high order discrete wavelet (db40) and comparing it with the classical methods, such as Fourier transform, applied in two conditions:

$$n_d \geq n_f + 2 \qquad (18)$$

n_f is the level of the detail

$$2^{-(n_d+1)} . f_s < f \qquad (19)$$

Cusido et al. (2006), according to the mistakes gotten from the FFT, introduced the spectral density on wavelet to detect many faults in the induction motor using same equations (13, 14 and 15) as an indication of faults for different load conditions (7 and 10%). As such, slip changing and the motor current signature analysis (MCSA) method was used for fault detection. The MCSA has a disadvantage especially when the load torque varies. Cusido et al. (2007, 2010) presented an on line system for fault detection using many wavelets like Mexican Hat, Morlet and Agnsis mother wavelet to detect a broken bar fault. The drawbacks of using FFT are investigated by many authors in detecting the rotor broken bar through db40 as a mother function to avoid the low level overlapping with adjacent bands. The decomposition levels are tested according to the following formula:

$$n_s = \frac{\log(fs/f)}{\log(2)} + 1 \qquad (20)$$

where f_s and f are the sampling and supply frequencies, respectively.

According to the following equation:

$$N_s = f_s / R \quad (21)$$

R is the resolution and N_s is the number of samples.

Hamidi et al. (2004) obtained a 0.1 Hz resolution to detect the faults in the induction motor using combination of wavelet and power spectral density. Douglas et al. (2003) and Douglas and Pillay (2005) presented fault detection in the transient region for the broken rotor bar using the instantaneous power FFT as a medium of fault detection and wavelet in decomposing the residual stator current after filtering the noise using Notch filter. Supangat et al. (2006, 2007) presented wavelet indicator for detecting the broken rotor bars by calculating the absolute values of the summed coefficients in the third pattern. The normalized wavelet was against the summation of the wavelet coefficient, the number of scales and the number of samples used. Samsi et al. (2006) used the V/F control method to detect the broken rotor bar in the induction motor, while the diagnosis decision according to the probability distribution differs in the operation statues of healthy and faulty motors. The difference in entropy is used as a measure of:

$$M(k) = \sum_{i=1}^{i=|\sum p^k|} \log_2 \left(\frac{p^k_i}{p^1_i} \right) \quad (22)$$

where p^k is the distribution corresponding to run k.

Riera et al. (2008) used DWT to detect the broken rotor bar in the transient region using slip dependant fault component according to the energy ratio of the current signal to the wavelet signal as in the following relationship:

$$\gamma_{\omega}(indb) = 10 \log \left[\frac{\sum_{j=Nb}^{Ns} i^2_j}{\sum_{j=Nb}^{Ns} [\omega n(j)]^2} \right] \quad (23)$$

Antonino-Daviu et al. (2006) presented the broken rotor bar fault detection using optimized DWT and FFT in the steady state. Kia et al. (2007, 2009) presented a DWT for broken bar detection and diagnosis faults in induction machines. However, the energy test of bandwidth with time domain analysis is the first step, before any other steps are applied to the stator current space vector to obtain the different broken bar fault severities and load levels.

ARTIFICIAL INTELLIGENCE TECHNIQUES

Artificial intelligence played an important role in the wavelet fault diagnosis and detection of induction motors, such as ANN, fuzzy logic, neuro-fuzzy and genetic algorithm. Abdesh et al. (2008) used the hybrid wavelet and neural network (WNN) to detect and classify the inverter's single phasing and shoot. However, the structure of the proposed network is shown in Figure 8 (Abdesh et al., 2008). Kyusung and Parlos (2002) used neuro predictor and wavelet to extract the non stationary signal feature in the transient stage for 2.2, 373 and 597 kW, using negative sequence as electric faults and the ratio as:

$$s(k) = \frac{r^{Ns}{}_h(k)}{I^{Ns}{}_h(k)} \quad (24)$$

Online detection of rotor bar faults had been done using wavelet with neural network after feature extraction with different resolution of the stator current (Zhongming et al., 2000, 2009). Guizhen et al. (2009) presented the neural wavelet and selected the Morlet wavelet function as the neural transfer function with new bias threshold and weights techniques to detect the asynchronous motor faults. Guang et al. (2009) presented a new fault diagnosis based on the collection of both WPA and hybrid support vector machine which give better results when compared with the classical BP.

Xinsheng and Kenneth (2004) dealt with the detection and diagnosis of a defect in ball bearings based on both WT and ANFIS classification. Zacharias et al. (2009) used the wavelet transform (WT) analysis with (ANN) for the detection and diagnosis of winding faults in electrical machines. Van Tung et al. (2009) presented a fault diagnosis method based on an adaptive neuro-fuzzy inference system (ANFIS) in combination with decision trees. Classification and regression tree (CART) is used as a feature selection tool to select features from data set. Vilas and Sanjay (2010) proposed an optimal MLP neural network based classifier for fault detection by employing the information obtained from the stator current. A detailed design procedure for MLP and the self organized map (SOM) of the NN models is thus given.

Singh et al. (2009) presented a treatment of the induction motor data obtained from physical parameters which are used to train the neural network. Achmad and Bo-Suk (2008) presented a new method of nonlinear kernel based on wavelet (W-SVM). Feature reduction and extraction, using the principal component analysis (PCA) and Kernal principal component analysis (KPCA) for the fault detection and diagnosis of induction motor, had been done in this work. Zhongming and Bin (2001) presented a novel method in detecting the broken rotor bar using the neural network with 4 layers (2 input layers, 1 hidden layer and 1 output layer), depending on the CFC

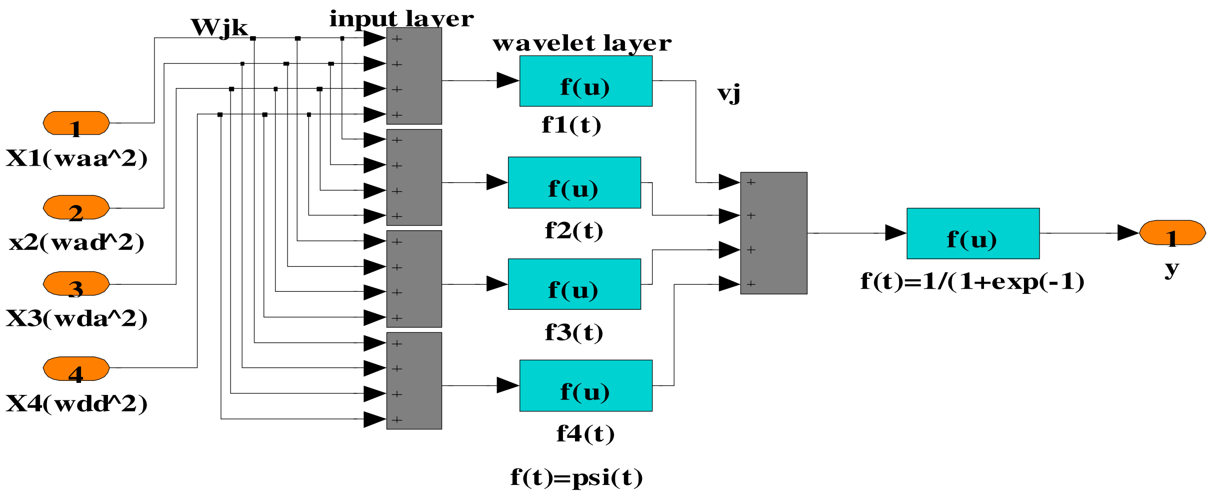

Figure 8. Structure of a three layer wavelet neural network.

of the location of *(1-2s) f* of the stator current. Qianjin et al. (2008) presented a detection of the rotor broken bar and stator inter-turn winding, using new methods that depend on MCSA technique generalized harmonic wavelet transform filter and hybrid particle swarm optimization (HPSO) based wavelet neural network.

Xu et al. (2009) presented a novel method used to detect the induction motor faults via wavelet neural with genetic for optimization. Karatoprak et al. (2008) used MWA to detect the vibration signals, while Shannon entropy was used to calculate the feature vectors. After that, the PCA used the probabilistic neural networks. Tan et al. (2007) proposed a neural and fuzzy hybrid, based on the integration of fuzzy ARTMAP (FAM) and the rectangular basis function network. This project was applied to the detection of the power generation station faults.

INVERTER FAULT DETECTION

In order to control the mechanical speed, the inverter is used to provide the induction motor with voltage of varying amplitude and frequency. In the last twenty years, the fault diagnoses of inverter faults have been given great importance. Here, some of the researches in this context by Khan et al. (2006) developed an online protection of the induction motor from (PWM-VSI) using DWT, for the induction motor controlled by fuzzy. Khanniche and Mamat (2001) presented a novel method used for detecting and identifying the transistor base drive open-circuit fault of the three-phase (VSI), using wavelet transform.

Dong-Eok and Dong-Choon (2008) presented DWT to detect the discontinuity of signal and then they used SVM to isolate the 3-phase PWM inverters.

Benslimane and Chetate (2006) presented a novel approach in identifying the inverter fault using wavelet transform of the stator current, whereas Bin and Sethom (2008) used the DWT and db as the mother wavelet to detect the misfiring of the PWM inverter supplying the induction motor.

APPLICATION OF WAVELET IN FAULT DETECTION

Stator short winding and stator open winding

To test the effectiveness of the wavelets, Daubechies (db10) with 6 levels decomposition were used as a sensitive tool to detect the fault in the induction motor. Two faults were simulated in this paper; the first was the stator open winding, and the second was the short winding. Parallel resistance should be connected with stator resistance to decrease the overall stator resistance. Consequently, the final stator resistance will be:

$$R_{short} = 0.1 R_{original} \tag{25}$$

For short winding, the series of three resistances should be connected with the stator resistance; as such, the open winding resistance will be:

$$R_{open} = 10 R_{original} \tag{26}$$

DISCUSSION

The wavelet was able to analyze and detect the faults subjected to the induction motor. The decomposition at

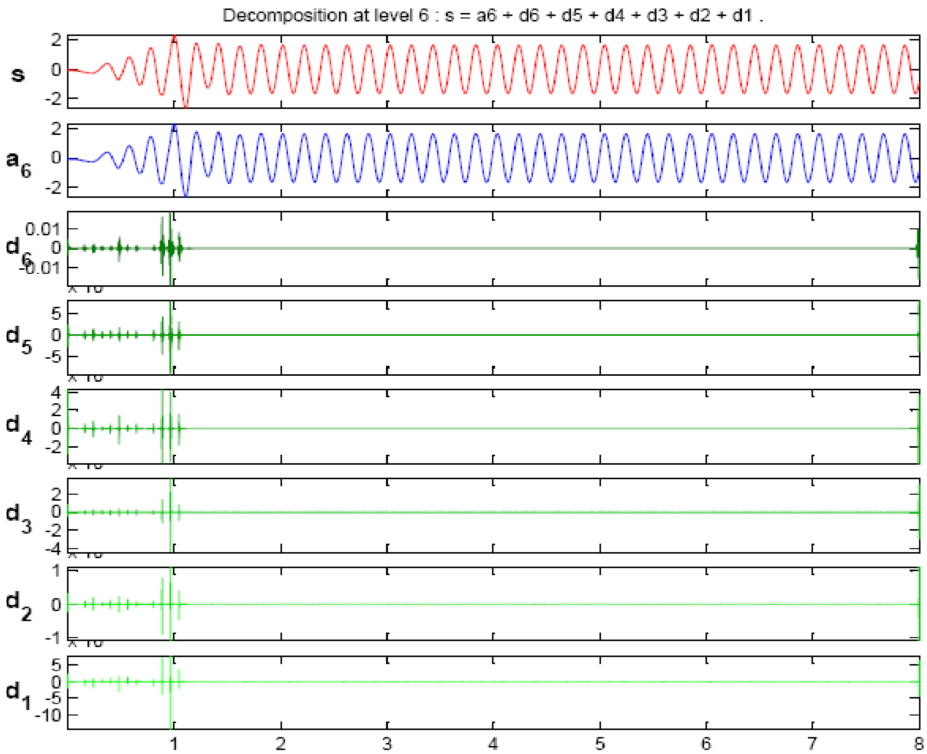

Figure 9. Decomposition at level 6 of the stator healthy induction motor.

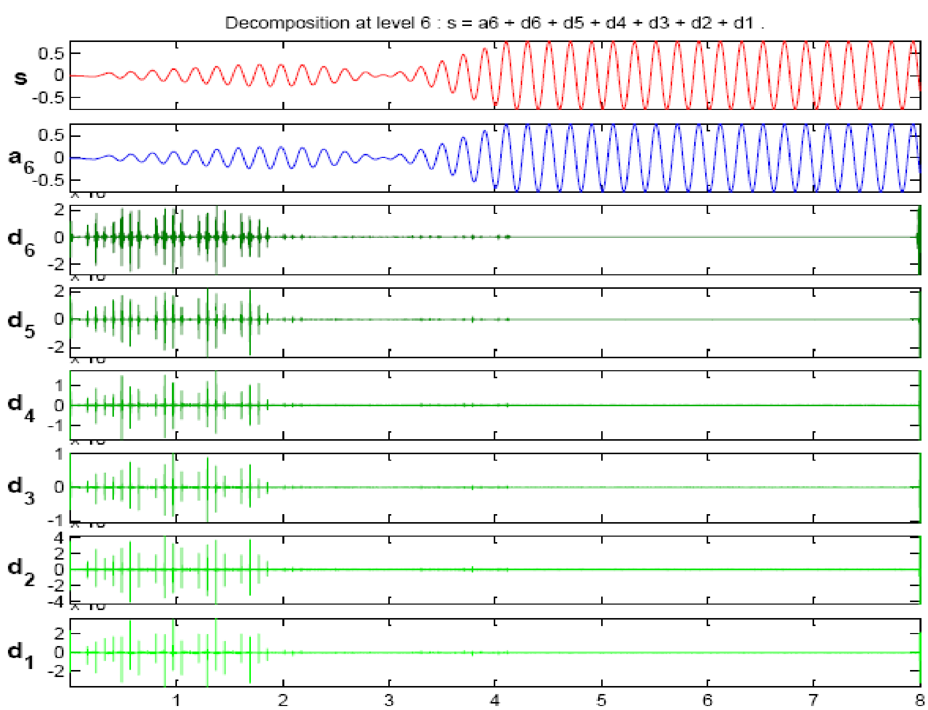

Figure 10. Decomposition at level 6 of the open winding.

level 6 is presented to ensure the best detection of both faults as it can be shown in Figures 9, 10, and 11 for healthy, opening, short winding, respectively. The current in the healthy case is exactly 1.7a, but with small

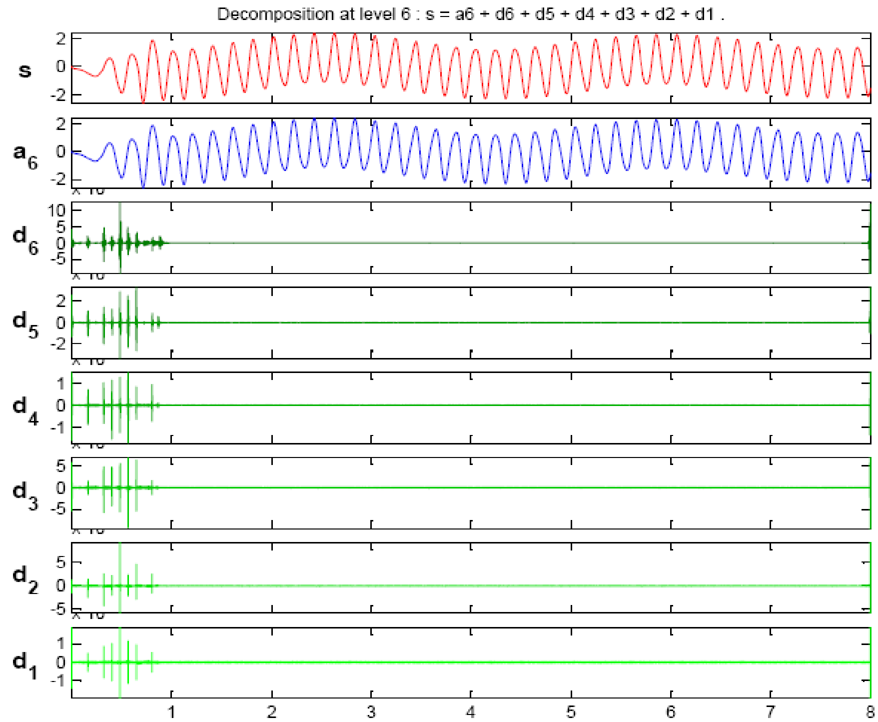

Figure 11. Decomposition at level 6 of the stator short winding.

Table 9. Threshold of wavelet levels in the healthy.

Decomposition level	Threshold
Level 6	0.22
Level 5	0.22
Level 4	0.22
Level 3	0.22
Level 2	0.22
Level 1	0.22

Table 10. Threshold of wavelet levels in open winding fault.

Decomposition level	Threshold
Level 6	1.954
Level 5	1.954
Level 4	1.954
Level 3	1.201
Level 2	0.759
Level 1	0.756

overshot in the transient region, while the amplitude of the stator current in the stator open winding is 0.75 a at a steady state and between -2a and +2a at an oscillation state. According to the approximations and details coefficients of the wavelet, the effectiveness of the wavelet to detect the fault in the stator winding is strong. Tables 9, 10 and 11 show the global threshold at the different levels for the same figures.

Table 11. Global threshold of wavelet levels in short winding fault.

Decomposition level	Threshold
Level 6	0.148
Level 5	0.148
Level 4	0.148
Level 3	0.148
Level 2	0.148
Level 1	0.096

CONCLUSION

This review is carried out on two important issues. First, is the fault tolerant control and second, is the wavelet in the induction motors fault diagnosis. There are many conclusions that can be drawn from this review:

1. The fault tolerant control is very important in the healthy systems, but not in the faulty system.
2. Fault diagnosis is the first step of fault tolerant control.

3. The knowledge about the induction motor frequency characteristics is very important in either the faulty or healthy case.
4. The wavelet is considered as a powerful tool in the fault detection and diagnosis of induction motors.
5. The improvement of fault detection and diagnosis can be exploited by the wavelet properties to get high detection and diagnostics effectiveness.
6. Theories of wavelet need to be pushed forward to ensure the best choice of mother wavelet.
7. The wavelet transform can be used to detect and identify the inverter faults.
8. The wavelet can distinguish correctly the faults and thermal effects that make the parameters such as resistance and inductance vary.

Conclusively, the wavelet can be used with any technique of the machine drive and control.

REFERENCES

Abbas ZK, Milimonfared J, Haji M, Toliyat HA (2001). Broken bar detection in induction motor via wavelet transformation.27th Annu. Conf. IEEE Ind. Electron. Soc. IECON., 1: 95–99.

Abdesh M, Khan SK, Azizur Rahman M (2008). A new wavelet based diagnosis and protection of faults in induction motor drives. IEEE Conf. Power Electron. Specialists, PESC, pp. 1536–1541.

Achmad W, Bo-Suk Y (2008). Wavelet support vector machine for induction machine fault diagnosis based on transient current signal." Expert Syst. Appl., 35: 307–316.

Amr S, Adel S, Mario P (2007). Fault Tolerant Field Oriented Control of Induction Motor for Loss of One Inverter Phase with Re-starting Capability. IEEE Int. Symp. Ind. Electron., pp. 1340-1345.

Amr S, Mario P, Adel S (2006). " Fault Tolerant Field Oriented Control of the Induction Motor for Loss of One Inverter Phase." IEEE, 32nd Annu. Conf. Ind. Electron., pp. 817–822.

Andrea P (2003). Fault Detection and Fault Tolerant Control for Distributed Systems. A General Framework .Ph.D thesis. University of Bologna, pp. 60-70.

Andrew K.S. Jardine, Daming Lin, Dragan Banjevic (2006).A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech. Syst. Signal Process., 20: 1483–1510.

Anjali PD, Sachin CP, Shankar SN (2008). Intelligent State Estimation for Fault Tolerant Nonlinear Predictive Control. J. Process. Control, 19(2): 187-204.

Antonino JA, Riera M, Roger-Folch J, Molina MP (2005).Validation of a new method for the diagnosis of rotor bar failures via wavelet transformation in industrial induction machines. 5th IEEE Int. Symp. Diagnost. Electric Machines, Power Electron. Drives, SDEMPED. DEMPED, pp. 1–6.

Antonino-Daviu JA, Riera-Guasp MFJR, Palomares MPM (2006). Validation of a new method for the diagnosis of rotor bar failures via wavelet transform in industrial induction machines.IEEE Trans. Ind. Appl., 42(4): 990–996.

Ayaz E, Ozturk A, Seker S (2006).Continuous Wavelet Transform for Bearing Damage Detection in Electric Motors." IEEE Electrotech. Conf. MELECON, Mediterranean, pp. 1130–1133.

Benslimane T, Chetate B (2006). New Diagnostic Method of Faulty Transistor in a Three Phase Inverter. J. Electri. Elect. Eng., 6(2): 117-128.

Bin L, Paghda M (2008). Induction motor rotor fault diagnosis using wavelet analysis of one-cycle average power" Twenty-Third Annual IEEE conf. Appl. Power Electron. Exposit. APEC, pp. 1113–1118.

Cabal YE,Osornio-Rios RA, Romero-Troncoso RJ, Razo-Hernandez. JR, Lopez-Garcia R (2009). FPGA-Based Online Induction Motor Multiple-Fault Detection with Fused FFT and Wavelet Analysis" Int. Conf. Reconfigurable Comput. FPGAs, pp. 101–106.

Campos-Delgado DU, Espinoza-Trejo DR, Palacios E (2008). Fault-tolerant control in variable speed drives: a survey. IET Electr. Power Appl., 2(2): 121–134.

Cao Z, Chen H, He G, Ritchie E (2001). Rotor fault diagnosis of induction motor based on wavelet reconstruction. Proc. Fifth Int. Conf. Electric. Machines Syst. ICEMS, 1: 374–377.

Chao-Ming C, Loparo KA (1998). Electric fault detection for vector-controlled induction motors using the discrete wavelet transform. Proc. Am. Control Conf., 6: 3297–3301.

Chia-Chou Y (2007). Fault Tolerant Operations in Adjustable-Speed Drives and Soft Starters for Induction Motors. IEEE Power Electron., 1942–1949.

Chinmaya K, Mohanty AR (2006). Monitoring gear vibrations through motor current signature analysis and wavelet transform. Mech. Syst. Signal Process., 20: 158–187.

Combastel C, Lesecq S, Petropol S, Gentil S (2002). Model-based and wavelet approaches to induction motor on-line fault detection. Cont. Eng. Pract., 10: 493–509.

Cunxiang Y, Guangzhao C, Yunbing W, Yongji W (2007). Fault Diagnosis for Induction Motors Using the Wavelet Ridge. Second International Conference on Bio-Inspired Computing. Theor. Appl. BIC-TA, pp. 231–235.

Cusido J, Jornet A, Romeral L, Ortega JA, Garcia A (2006). Wavelet and PSD as a Fault DetectionTechniques. Proc. IEEE Conf. Instrum. Meas. Technol. IMTC, pp. 1397–1400.

Cusido J, Romeral L, Ortega JA, Garcia A, Riba JR (2010). Wavelet and PDD as fault detection techniques." Electric Power Syst. Res., EPSR-3012.

Cusido J, Romeral L, Ortega JA, Rosero JA, Garcia EA (2008). Fault Detection in Induction Machines Using Power Spectral Density in Wavelet Decomposition. IEEE Trans. Ind. Electron., 55(2): 633–643.

Cusido J, Rosero JA, Cusido M, Garcia A, Ortega JA, Romeral L (2007). On-Line System for Fault Detection in Induction Machines Based on Wavelet Convolution. IEEE Conf. Instrum. Meas. Technology.IMTC., 1 – 5.

Cusido J, Rosero JA, Cusido M, Garcia A, Ortega JA, Romeral L, Author Q (2007). " On-Line System for Fault Detection in Induction Machines based on Wavelet Convolution" IEEE Conf. Power Electron. Specialists, PESC, pp. 927–932.

Cusido J, Rosero JA, Ortega JA, Garcia A, Romeral L (2006). Induction Motor Fault Detection by using Wavelet decomposition on dq0 components. IEEE Int.Symp. Ind. Electron., 3: 2406–2411.

Cusido J, Rosero JA, Romeral L, Ortega JA, Garcia A (2006). Fault Detection in Induction Machines by Using Power Spectral Density on the Wavelet Decompositions. 37th IEEE Conf. Power Electron. Specialists, PESC, pp. 1–6.

Cusido LR, Garcia A, Rosero JA, Ortega JA (2007). Fault detection in induction machines by using continuous and discrete wavelet decomposition. Eur. Conf. Power Electron. Appl., pp. 1–8.

Dong-Eok K, Dong-Choon L (2008). Fault Diagnosis of Three-Phase PWM Inverters using Wavelet and SVM. IEEE Int. Symp. Ind. Electron. ISIE, pp. 329–334.

Douglas H, Pillay P (2005). The impact of wavelet selection on transient motor current signature analysis. IEEE Int. Conf. Electric Machines Drives, 80–85.

Douglas H, Pillay P, Ziarani A (2003). Detection of broken rotor bars in induction motors using wavelet analysis. IEEE Conf. Electric Machines Drive, IEMDC'03 Int., 2: 923–928.

Eren L, Devaney MJ (2002). Bearing damage detection via wavelet packet. Proc. 19th IEEE Instrum. Meas. Technol. Conf., pp. 109–113.

Eren L, Teotrakool K, Devaney MJ (2007).Bearing Fault Detection via Wavelet Packet Decomposition with Spectral Post Processing. IEEE Conf. Proc. Instrum. Meas. Technol. IMTC., pp. 1–4.

Fekih A, Pilla P (2009). A New Fault Tolerant Control Strategy for Aircraft Systems under Adverse Flying Conditions. J. Automat. Syst. Eng., 3(1): 1-16.

Jacobina CB, Freitas IS, Oliveira TM, da Silva ERC, Lima AMN (2004). Fault Tolerant Control of Five-Phase AC Motor Drive. 35th Annu. IEEE Power Electron. Specialists Conf., 5: 3486–3492.

Mendes AMS, Marques CAJ (2003). Three-phase Induction Motor

Drives under Inverter Fault Conditions. SDEMPED Symposium on Diagnostics for Electric Machines, Power Electronics and Driver Allanla. CA. USA, pp. 24-26.
Faiz J, Ebrahimi BM, Asaie B, Rajabioun R, Toliyat HA (2007). A criterion function for broken bar fault diagnosis in induction motor under load variation using wavelet transform.Int. Conf. Electric. Machines Syst. ICEMS, pp. 1249–1254.
Gang N, Achmad W, Jong-Duk S, Bo-Suk Y, Don-Ha H, Dong SK (2008). Decision-level fusion based on wavelet decomposition for induction motor fault diagnosis using transient current signal. Expert Syst. Appl., 35: 918–928.
Singh GK, Sa'ad A, Ahmed SA (2009). Isolation and identification of dry bearing faults in induction machine using wavelet transform. Tribol. Int., 42: 849–861.
Guizhen Z, Guorong L, Yiping L (2009). Asynchronous Motor Fault Diagnosis Based on Wavelet Neural Network. Int. Conf. Inf. Eng. Comput. Sci., ICIECS, pp. 1–4.
Guang MX, Bi-Qing Z (2009). An intelligent fault diagnosis method based on wavelet packer analysis and hybrid support vector machines.Expert Syst. Appl., 36: 12131–12136.
Hamidi H, Nasiri AR, Nasiri F (2004). Detection and isolation of mixed eccentricity in three phase induction motor via wavelet packet decomposition. Control Conf. 5th Asian, 2: 1371–1376.
Halim A, Christopher E (2008). Fault Tolerant Control using Sliding Modes with on-line Control Allocation. Automatica, 44: 1859–1866.
Bin AH, Sethom MA (2008). Intermittent Misfiring Default Detection and Localization on a PWM Inverter Using Wavelet Decomposition." J. Elect. Syst., 4(2): 1-12.
Haider AF, Mohamed SS, Yang MM (2008). Sliding Mode Sensor Fault Tolerant Control Structure for Induction Motor. IEEE, SICE, pp. 2630-2635.
Nademi H, Tahami F, Rezaei M (2008). Fault Tolerant IPMS Motor Drive Based on Adaptive Back stepping Observer with Unknown Stator Resistance. 3rd IEEE Conf. Ind. Electron. Appl., pp. 1785-1790.
Hui-Wei L, Jia-Cheng L, Wei-Wei C (2008). Adaptive Fault Tolerant Control for a Class of Inherent Nonlinear Systems. IEEE, Control Decis. Conf., pp. 541–545.
Antonino-Daviu J, Jover RP, Riera-Guasp M, Arkkio A, Roger-Folch J, Perez RB (2009). Transient detection of eccentricity-related components in induction motors through the Hilbert–Huang Transform. Ener. Conver. Manage., 50: 1810–1820.
Antonino-Daviu J, Riera-Guasp M, Roger-Folch J, Martinez-Gimenez F, Peris A (2006). Application and optimization of the discrete wavelet transform for the detection of broken rotor bars in induction machines. Appl. Comput. Harmon. Anal., 21: 268–279.
Antonino-Daviu J, Jover RP, Riera-Guasp M, Pineda-Sa´nchez M, Arkkio A (2009). "Detection of combined faults in induction machines with stator parallel branches through the DWT of the startup current." Mech. Syst. Signal Process., 23: 2336–2351.
Jafar Z, Javad P (2007). Bearing fault detection using wavelet packet transform of induction motor stator current. Tribol. Int., 40: 763–769.
Jawad F, Mansour O (2009). Different indexes for eccentricity faults diagnosis in three-phase squirrel-cage induction motors: A review. Mechatronics, 19: 2–13.
Jean-Etienne D, Harry GK, Gaurav B, Carole T (2007). Variable Structure Design of a Fault Tolerant Control System for Induction Motors. IEEE, Electric Ship Technol. Symp., pp. 531–535.
Rafiee J, Rafiee MA, Tse PW (2010). Application of mother wavelet functions for automatic gear and bearing fault diagnosis. Expert Syst. Appl., 37: 4568–4579.
Karatoprak E, Senguler T, Seker S (2008). Using probabilistic neural networks with wavelet transform and principal components analysis for motor fault detection. IEEE 16th Signal Process. Commun. Appl. Conf. SIU, pp. 1–4.
Khalaf SG, Hew WP, Haider AFM (2010). Diagnosis and Fault Tolerant Control of the Induction Motors Techniques: A review. Aust. J. Basic Appl. Sci., 4(2): 227-246.
Khalaf SG, Hew WP (2010).Induction motor fault detection and isolation through unknown input observer. Sci. Res. Essays, 5(20): 3152-3159.
Khan MASK, Rahman MA (2006). Discrete Wavelet Transform Based Detection of Disturbances in Induction Motors. Electric. Comput. Eng. ICECE, pp. 462–465.
Khan MASK, Radwan TS, Rahman MA (2006). Wavelet Based Diagnosis and Protection of Three-Phase Induction Motor Fed from Sinusoidal PWM Voltage Source Inverter. The 3rd IET International Conference on Power Electronics, Machines and Drives, pp. 226–230.
Kia SH,Henao H, Capolino GA (2009). Diagnosis of Broken-Bar Fault in Induction Machines Using Discrete Wavelet Transform without Slip Estimation. IEEE Trans. Ind. Appl., 45(4): 1395-1404.
Kia SH, Henao H, Capolino SGA (2007). Diagnosis of Broken Bar Fault in Induction Machines Using Discrete Wavelet Transform without Slip Estimation. IEEE Conf. Record Ind. Appl., 42nd IAS Annu. Meet., pp. 1917–1922.
Kyusung K, Parlos AG (2002). "Induction motor fault diagnosis based on neuro predictors and wavelet signal processing." IEEE/ASME Trans. Mechatron., 7(2): 201–219.
Lorand S, JenoBarna D, Karoly Agoston B (2005). Discrete Wavelet Transform Based Rotor Faults Detection Method for Induction Machines. Intell. Syst. Service Mankind, 2: 63-74.
Matthew OTC, Patrick SK, Mehmet NS, Clifford RB (2004). Towards Fault-Tolerant Active Control of Rotor–Magnetic systems. Control Eng. Pract., 12: 491–501.
Mohammed OA, Abed NY, Ganu S (2006). Modelling and Characterization of Induction Motor Internal Faults Using Finite-Element and Discrete Wavelet Transforms. IEEE Trans. Magnet., 42(10): 3434–3436.
Mohammed OA, Abed NY, Garni S (2007). Modeling and characterization of induction motor internal faults using finite element and discrete wavelet transforms. IEEE Symp. Electric Ship Technol., ESTS, pp. 250–253.
Riera-Guaspa M, Antonino-Daviua J, Rusekb J, Roger-Folch J (2009). Diagnosis of rotor asymmetries in induction motors based on the transient extraction of fault components using filtering techniques. Electric Power Syst. Res., pp. 1181–1191.
Khanniche MS, Mamat Ibrahim MR (2001). Fault Detection and Diagnosis of 3-Phase Inverter System.UK. Power Eng., pp. 69-75.
Niklas G (2003). Wavelet software overview and comments. Lecture notes, pp. 1-19.
Ordaz Moreno A, de Jesus R, Vite-Frias R (2008). Automatic Online Diagnosis Algorithm for Broken-Bar Detection on Induction Motors Based on Discrete Wavelet Transform for FPGA Implementation. IEEE Trans. Ind. Electron., 5(5): 2193–2202.
Pons-Llinares J, Antonino-Daviu JA, Riera-Guasp M, Pineda-Sanchez M, Climente-Alarcon V (2009). Induction motor fault diagnosis based on analytic wavelet transform via Frequency B-Splines. IEEE Int. Symp. Diagnost. Electric Mach., Power Electron. Drives, SDEMPED, pp. 1–7.
Pineda-Sanchez M, Riera-Guasp M, Antonino-Daviu JA, Roger-Folch J, Perez-Cruz J, Puche-Panadero R (2009). Diagnosis of Induction Motor Faults in the Fractional Fourier Domain. IEEE Trans. Instrum. Meas., 59(8): 2065-2075.
Ponci F, Monti A, Cristaldi L, Lazzaroni M (2007). Diagnostic of a Faulty Induction Motor Drive via Wavelet Decomposition. IEEE Trans. Instrum. Meas., 56(6): 2606–2615.
Qiao H, Zhengjia H, Zhousuo Z, Yanyang Z (2007). Fault diagnosis of rotating machinery based on improved wavelet package transform and SVMs ensemble. Mech. Syst. Sig. Process., 21: 688–705.
Qianjin G, Xiaoli L, Haibin Y, Xiangzhi C, Wei H, Jingtao H (2008).Fault Monitoring and Diagnosis of Induction Machines Based on Harmonic Wavelet Transform and Wavelet Neural Network. Int. Conf. Nat. Computat., ICNC., 4: 140–146.
Rong-Jong W, Jia Ming C (2002). Intelligent control ofinduction servo motor drive via wavelet neural network. Electric. Power Syst. Res., 61(1): 67-76.
Romero M, Seron E, Maria De D, Jose A (2009). Sensor Fault Tolerant Direct Torque and Flux Control of Induction Motor.17th IFAC symposium on fault detection ,supervision, and safety of technical processes, SAFEPROCESS'09, Bercelona, Spain.
Rui Z, Wen B, Ning L, Xin H, Daren Y (2010). Mechanical equipment fault diagnosis based on redundant second generation wavelet packet transform. Dig. Sig. Process., 20: 276–288.

Salehi AR, Jalilian A (2010). Design, Implementation and Comparison of Two Wavelet Based Methods for the Detection of Broken Rotor Bars in Three Phase Induction Motors.1st Power Electr. Drive Syst. Technol. Conf. (PEDSTC), pp. 345–350.

Ron JP (1997). Fault Tolerant Control Systems: The 1997 Situation. Univ. Hull, Sch. Eng., Hull HU6 7RX, UK.

Riera-Guasp M, Antonino-Daviu JA, Pineda-Sanchez M, Puche-Panadero R, Perez-Cruz J (2008). A General Approach for the Transient Detection of Slip-Dependent Fault Components Based on the Discrete Wavelet Transform. IEEE Trans. Ind. Electr., 55(12): 4167–4180.

Abbasiona S, Rafsanjania A, Farshidianfarb A, Irani N (2007). Rolling element bearings multi-fault classification based on the wavelet de-noising and support vector machine. Mech. Syst. Sig. Process., 2: 2933–2945.

Saleh SA, Khan MA, Rahman MA (2005). Application of a wavelet-based MRA for diagnosing disturbances in a three-phase induction motor. 5th IEEE Conf. Diagn. Elect. Mach. Power Electr. Drives, SDEMPED., pp. 1–6.

Samsi R, Rajagopalan V, Ray A (2006). Wavelet-based symbolic analysis for detection of broken rotor bars in inverter-fed induction motors. IEEE Conf . Cont., ThB07.3: 3032-3037.

Sang-Hyuk L, Seong-Pyo C, Yountae K, Sungshin K (2006). ICIC'06 Proceeding. Part II: 557-569.

Bodkhe SB, Aware MV (2009). Speed sensorless, adjustable-speed induction motor drive based on dc link measurement. Int. J. Phys. Sci., 4(4): 221-232.

Tan SC, Lim CP, Rao MVC (2007). A hybrid neural network model for rule generation and its application to process fault detection and diagnosis. Eng. Appl. Artif. Intell., 20: 203–213.

Sejir K, El K, Ilhem S, Belkhodja MP, David BdeF (2006). A Fault Tolerant Operating System in a Doubly Fed Induction Machine Under Inverter Short-circuit Faults. IEEE, 32nd Annu. Conf. Ind. Electr., IECON., pp. 1125-1130.

Serhat S, Emine A (2003). Feature extraction related tobearing damage in electric motors by wavelet analysis. J. Franklin Inst., 340: 125–134.

Serhat S, Gullulu S, Ayaz E (2008).Transfer Function approach based upon wavelet transform for bearing damage detection in electric motors. IEEE Int. Symp. Ind. Elect., ISIE., pp. 749–752.

Ghoshal SK, Samantaray AK, Samanta S (2009). Model Based Fault Diagnosis ,Fault Tolerant Control and Reconfiguration of Hydraulic and Thermo Fluid using Analytical Redundancy. Int. J. Autom. Cont. (IJAAC), 3(4): 363-384.

Vukosavic SN, Jones M, Levi E, Varga J (2005). Rotor Flux Oriented Control of a Symmetrical Six-Phase Induction Machine. Elec. Power Syst. Res., 75: 142–152

Radhika S, Sabareesh GR, Jagadanand G, Sugumaran V (2010). Precise wavelet for current signature in 3φ IM. Exp. Syst. Appl., 37: 450–455.

Stoyan K (2004). Robust Fault Tolerant Control.Ph.D. Thesis, University of Twente, Netherlands.

Supangat R, Ertugrul N, Soong WL, Gray DA, Hansen C, Grieger J (2006). Detection of broken rotor bars in induction motor using starting-current analysis and effects of loading. IEE Proc. Electr. Power Appl., 153(6): 848 – 855.

Supangat R, Grieger J, Ertugrul N, Soong WL, Gray DA, Hansen C (2007). Detection of Broken Rotor Bar Faults and Effects of Loading in Induction Motors during Rundown. IEEE Int. Conf. Electr. Mach. Drives, IEMDC., 1: 196–201.

Teotrakool K, Devaney MJ, Eren L (2007). Adjustable-Speed Drive Bearing-Fault Detection via Wavelet Packet Decomposition. IEEE Trans. Instrum. Meas., 58(8): 2747–2754.

Tong L, Jin H (2005). A novel method for induction motors stator interturn short circuit fault diagnosis by wavelet packet analysis. Proc. Eighth Int. Conf. Electr. Mach. Syst., ICEMS., 3: 2254–2258.

Tsoumas I, Mitronikas E, Safacas A (2005). "Induction motor mixed fault diagnosis based on wavelet analysis of the current space vector." Eighth Int. Conf. Electr. Mach. Syst., CEMS., 3: 2186–2191.

Van Tung T, Bo-Suk Y, Myung-Suck OH, Andy Chit CT (2009). Fault diagnosis of induction motor based on decision trees and adaptive neuro-fuzzy inference. Exp. Syst. Appl., 36: 1840–1849.

Vilas NG, Sanjay VD (2010). Optimal MLP neural network classifier for fault detection of three phase induction motor. Exp. Syst. Appl., 37: 3468–3481.

Wai-Chuen G, Li Q (2003). Compensator: An Application to Indirect-Field-Oriented-Control Induction Machine Drive. IEEE Ind. Electr., 50(2): 272–282.

Xiaodong Z (2002). Fault Diagnosis and Fault Tolerant Control in Nonlinear Systems. Ph.D Thesis University of Cincinnati.

Xinsheng L, Kenneth AL (2004). Bearing fault diagnosis based on wavelet transform and fuzzy inference. Mech. Syst. Sig. Process., 18: 1077–1095.

Yixiang H, Chengliang L, Xuan FZ, Yanming L (2010). A lean model for performance assessment of machinery using second generation wavelet packet transform and Fisher criterion. Exp. Syst. Appl., pp. 3815–3822.

Xu LY, Wan NL (2009). Motor Fault Diagnosis Based on Wavelet Neural Network." Int. Conf. Intell. Comput. Technol. Autom., ICICTA., 2: 553–555.

Youmin Z, Jin J (2008). Bibliographical Review on Reconfigurable Fault Tolerant Control Systems. Ann. Rev. Cont., 32: 229–252.

Zacharias EG, Michalis EZ, George S (2009). Detection and classification of winding faults in windmill generators using Wavelet Transform and ANN. Electr. Power. Syst. Res., 79: 1483–1494.

Zhongming Y, Bin W, Zargari N (2000). Online mechanical fault diagnosis of induction motor by wavelet artificial neural network using stator current. 26th IEEE Annu. Conf. Electr. Soc. IECON., 2: 1183–1188.

Zhang J, Zhu N, Yang L, Yao Q, Lu Q (2007). A Fault Diagnosis Approach for Broken Rotor Bars Based on EMD and Envelope Analysis. J. China Univ. Min. Technol., 17(2): 205-209.

Zhongming Y, Bin W (2001). Online rotor bar breakage detection of three phase induction motors by wavelet packet decomposition and artificial neural network. IEEE 32nd Annu. Conf. Power Electr. Specialists, 4: 2209–2216.