Fault detection in VSD-fed induction motors through Park's impedance and fuzzy systems

Arturo Mejia Barron

Universidad Autónoma de Querétaro, San Juan del Rio, C.P. 76807, Qro., México

amejia@hspdigital.org

Armando Guadalupe Garcia Ramirez

Universidad Autónoma de Querétaro, San Juan del Rio, C.P. 76807, Qro., México

aggarcia@hspdigital.org

Roque Alfredo Osornio Rios

Universidad Autónoma de Querétaro, San Juan del Rio, C.P. 76807, Qro., México

raosornio@hspdigital.org

Rene de Jesus Romero Troncoso

Universidad de Guanajuato, Salamanca, C.P. 36885, Gto., México

raosornio@hspdigital.org

Summary

Industrial applications that require speed control have been increasing in recent years and the use of variable speed drives (VSD) for feeding induction motors (IM) is more common. Therefore, methodologies for detecting faults on VSD-fed IM are needed with the aim of minimize cost in maintenance and reduce the power consumption. In this work a methodology for fault diagnosis is proposed through spectral patterns obtained from the Park's impedance. Broken rotor bar, unbalanced mass, and misalignment conditions are investigated and a fuzzy-logic diagnosis system is proposed for asserting the VSD-fed IM condition. Results show high effectiveness in detection of the

investigated fault conditions through the proposed methodology, which has been validated with experimental tests.

Index terms: fault detection, impedance analysis, induction motors, park transform, variable speed drives.

1. Introduction

Predictive maintenance is one of the most important concerns in industry because it helps to detect faults in industrial processes, granting a major equipment useful life, lower cost production, and a uniform end-product quality by avoiding line stops [1]. Induction motors (IM) are the most widely used electrical machine in industry. Due to its simple structure and high reliability, the IM is used for many purposes such as pumps, blowers, fans, compressors, transportation, machinery spindles, etc. IM is the most typical and representative equipment in modern production system, which consumes more than 50% of the electrical energy used in industry [2]. Owning to thermal, electrical and mechanical stresses, mechanical and electrical failures are unavoidable in IM. Early detection of abnormalities in the motor helps to avoid expensive failures [3]. Around 40% to 50% of IM faults are bearing related, rotor faults represent 5% to 10% and unbalance and misalignment faults are about 12% [4]. Furthermore, variable-speed applications have been increasing recently, so the connection of IM through variable speed drives (VSD) is required. This connection can provide some advantages like extending the IM useful life and saving energy, but making the detection of faults more difficult due to the spurious harmonics induced by the VSD operation [5]. Moreover, the extensive use of VSD allows new possibilities for the on-line detection of faults [6].

Concerning to fault detection in IM, a number of techniques have been proposed. Signal processing approaches like fast Fourier transform (FFT), current envelope, multiple reference frame theory, discrete wavelet transform (DWT), continuous wavelet transform (CWT), rough set theory based classifier, Park transform, cross wavelet transform (CWT), extended Park vector, Concordia pattern, empirical-mode decomposition (EMD), short-time Fourier transform (STFT), multiple signal classification (MUSIC) as well as different AI techniques have been used for fault diagnosis and severity evaluation [7]. The appropriate monitoring method depends on the operating conditions of the motor. Otherwise, several techniques for the diagnosis of multiple faults have been proposed; Garcia-Perez et al. [4] proposed a methodology combining a filter bank of finite impulse response (FIR) filters along with high resolution spectral analysis based on MUSIC for detecting multiple combined faults, using current and vibration signals, the results show the analytical frequency location for single , two or three combined faults (broken rotor bars, unbalance mass and bearings damage). Soualhi et al. [8] carried out a fault detection methodology based on artificial ant clustering through multiple features extracted from motor current signature analysis (MCSA) and transformations made on current and voltage signals are used to obtain information for fault classification of broken rotor bars (BRB) and bearing damage (BD). Garcia-Ramirez et al. [9] performed an FPGA-based smart sensor in VSD-fed IM through current Park transform and an Artificial Neural Network (ANN) for automatic detection of faults such as BRB, unbalanced mass (UNB) and misalignment condition (MAL). Likewise, noninvasive analysis based on thermographic image segmentation for fault detection in IM have been carried out for BD, BRB, UNB and MAL conditions, through the analysis of the thermal steady-state of the kinematic chain, where criteria are proposed to evaluate a damage [10]. On the other hand, Romero-Troncoso et al. [11] presented a comparative study and evaluation of different condition monitoring methods accomplished for VSD-fed IM, with the aim of early BRB detection by steady-state current spectrum analysis, where MUSIC and the combination of EMD plus MUSIC methodologies are able to detect most faulty conditions, even in the early stage, when the motor is fed through VSD or the line supply. Delgado et al. [12] shows two methodologies for BD condition focused in non-invasive techniques Motor Current Signature Analysis (MCSA) based on temporal and frequency domain in which was verified that through frequency domain analysis is possible diagnose the bearings state by means of a fundamental frequency tracking. Regarding the unbalanced mass condition (UNB), Kral et al. [13] implemented a technique to sense the specific modulation of the electric power of faults such as eccentricities as well as load torque perturbation without using frequency spectrum. Gritli et al.[14] Propose a vibration analysis for mechanical unbalance detection under time-varying conditions based on advanced DWT method. Moreover, MAL condition has been computed by FFT extracting vibration features exhibited in the full spectrum. Otherwise, methods based on impedance analysis have been proposed, zero and negative sequence impedance features have been used for detecting eccentricity, missing wedge, inter-turn faults [15]–[17]. Lee et al. [17] perform a sensorless technique for on-line stator winding turn fault detection based on monitoring off-diagonal term of sequence component impedance matrix. Most of the methodologies aforementioned for fault detection are based in the stator current signal which is recommended for monitoring the IM and VSD-fed IM conditions and some signal components are used for fault diagnosis. The combination of two voltages and current signals of the IM can be suggested as an appropriate procedure for fault diagnosis in the VSD-fed IM [18].

In this work a methodology based on the combination of voltage and current signals through the Park transform components is proposed for detecting faults in IM fed through VSD, covering operating frequencies from 3Hz up to 60Hz. The proposed methodology is based on the spectrum analysis of Park's impedance which relates Park's voltages and currents. The amplitude of the fundamental frequency and the spectrum energy are calculated to be the input parameters of a fuzzy classifier, which gives the identification of the fault. In this work three different faults in IM are investigated: broken rotor bar (BRB), unbalanced mass (UNB) and misalignment (MAL). Then, the effectiveness of the proposed method is presented.

This work is organized as follows: the section 2 present a briefly review of the mathematical algorithms used in this work (Park transform, spectral analysis through FFT) and the induction motor conditions studied. Section 3 suggest a methodology to obtain the Park impedance through voltage and current signals, spectral parameters are obtained by mean to spectral analysis and a fuzzy logic system is proposed to identify the induction motor condition. Section 4 describes the components for the experimental setup and the fuzzy logic system for fault identification. Finally, section 5 and 6 present the obtained results of the proposed methodology, where the effectiveness of the classification system is showed for each operation condition.

2. Theoretical background

2.1. Park transform

The Park transform permits to express the three current or voltage phases of an IM through a two-axis system in quadrature. The components of this system: direct and quadrature (D and Q), are given by (1) and (2), respectively.

$$D = \sqrt{\frac{2}{3}}x_A - \sqrt{\frac{1}{6}}x_B - \sqrt{\frac{1}{6}}x_C \qquad (1)$$

$$Q = \sqrt{\frac{1}{6}}x_B - \sqrt{\frac{1}{6}}x_C \qquad (2)$$

Where x_A, x_B and x_C are the three phases stator currents (i_A, i_B and i_C) or voltages (v_A, v_B and v_c) [19].

2.2. Spectral analysis

The fast Fourier transform (FFT) is an efficient implementation of the discrete Fourier transform (DFT) given by (3), the most used technique for spectral analysis. Of all the discrete transforms, DFT is most widely used in digital signal processing. The DFT maps a sequence x(n) into the frequency domain X(k) [20].

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-\frac{j2\pi nk}{N}} \quad k = 0, 1, \ldots, N-1 \qquad (3)$$

Where $X(k)$ is the discrete signal and *N* is the number of points of DTF. The FFT provides a frequency spectrum, from 0 Hz to the sampling frequency.

2.3. Fuzzy logic based diagnosis approach

Diagnosis systems are used to monitor the behavior of a process and to identify certain patterns associated with well-known problems. Most diagnosis systems are in the form of a rule-based expert system, where a set of rules is used to describe certain patterns. Observed data are collected and used to evaluate these rules. If the rules are logically satisfied, the pattern identified, and the problem associated with the pattern is suggested. In general, the diagnosis systems are used as a tool for avoiding human expert consulting. Fuzzy logic is a tool which permits the system diagnosis on an easy way due to its simplicity [21].

2.4. Induction motor faults

In this work, three fault condition are considered: misalignment (MAL), unbalance mass (UNB) and broken rotor bar (BRB). The MAL condition is presented when the motor and the load pulleys are not aligned, it is the second most commonly fault in rotating machines [22]. Concerning UNB condition, it is presented when the rotor weight is not uniformly distributed around its geometrical center [13]. The BRB condition consist of a total or partial breakage of bars inside the armor rotor, it appears because of welding defects, high strength joints expansion an mechanical stresses [23].

3. Methodology

The proposed methodology as shown in Fig. 1 is based on the estimation of the impedance through the magnitude of the Park components D-Q of the current and voltage signals. Park's impedance is calculated through Park's current and voltage magnitude of the D-Q components for each k sample. These magnitudes of the Park current (i_{DQ-k}) and voltage (v_{DQ-k}) are calculated by (4) and (5) respectively.

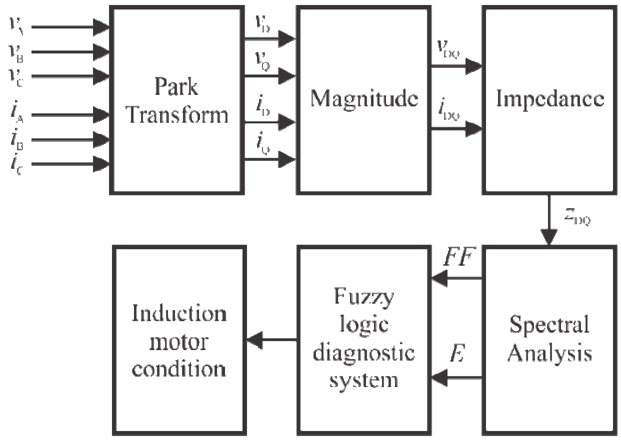


Fig. 1. Block diagram of the proposed methodology for induction motor fault detection.

$$i_{DQ-k} = \sqrt{i_{D-k}^2 + i_{Q-k}^2} \tag{4}$$

$$v_{DQ-k} = \sqrt{v_{D-k}^2 + v_{Q-k}^2} \tag{5}$$

Where i_{D-k}, i_{Q-k} , v_{D-k} and v_{Q-k} are the Park D-Q components of current and voltage respectively. Then the Park's impedance (z_{DQ-k}) is estimated from i_{DQ} and v_{DQ} obtained each sample k by (6).

$$z_{DQ-k} = \frac{v_{DQ-k}}{i_{DQ-k}} \tag{6}$$

A spectral analysis of the Park impedance is carried out through fast Fourier transform (FFT) to obtain fundamental frequency amplitude and the sum of energy in the frequency domain as inputs for the proposed fuzzy logic diagnostic system. The amplitude of the fundamental frequency (FF) is obtained through Park's impedance spectrum as shows in Fig. 2, meanwhile the sum of the energy in frequency domain (E_X) is obtained by (7).

$$E_X = \frac{1}{N}\sum_{k=0}^{N-1}|X(k)|^2 \tag{7}$$

Where *N* is the FFT number of points.

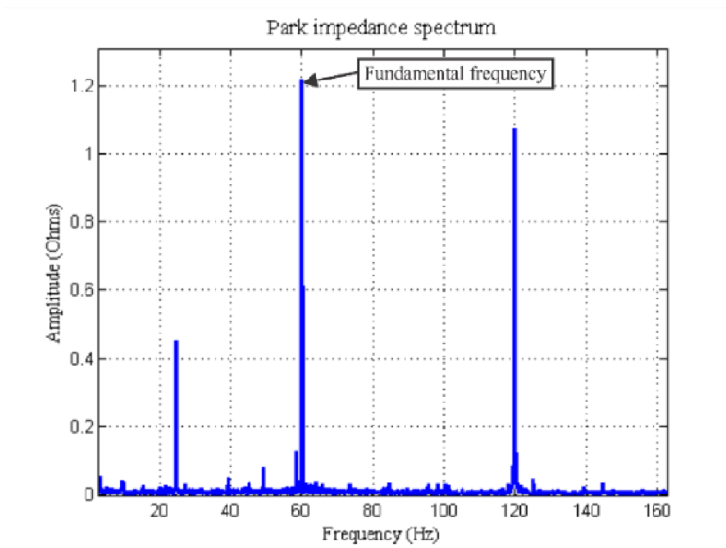


Fig. 2. Park impedance spectrum with a operation frequency of 60 Hz.

3.1. Proposed fuzzy logic diagnosis system

The proposed fuzzy logic diagnosis system has two inputs: the amplitude for the fundamental frequency and the spectral energy. Three fuzzy logic diagnosis systems are proposed for each operation frequency: 3Hz, 30Hz and 60Hz to obtain a wide-range of operation frequency. The fuzzy logic diagnosis systems returns the operation condition: healthy condition (HLT), misalignment (MAL), unbalance (UNB) and broken rotor bars (BRB).

4. Experiment

4.1. Experimental setup

The current and voltage signals during the steady state are obtained and used for detecting classifying the faults; these signals are provided by a VSD (model WEG CFW08) connected to the induction motor. The VSD has an operating range from 0Hz to 100Hz using a frequency resolution of 0.01Hz. The experimental setup is shown in Fig. 3 where 1-hp (735.5 W), three-phase induction motor (model WEG 00136APE48T) is used to test the performance of the proposed methodology to identify the fault conditions considered in this work. The tested motor has two poles and twenty eight bars. The rotational speed of the motor is set by a VSD operating at 3Hz, 30Hz and 60Hz during the steady state. The applied mechanical load is from an ordinary alternator, which represents a quarter of the nominal load for the motor. The three-phase current signals are acquired using three hall-effect sensors model L08P050D15, from Tamura Corporation with an accuracy of ±1% and an output linearity of ≤±1%. On the other hand, voltage signals are acquired on each phase by a voltage divider and a precision isolation amplifier model ISO124PND from Texas Instruments Inc., in order to get a galvanic isolation between the power systems as the proposed monitoring system. A 16-bit 4-channel serial-output sampling analog-to-digital converter ADS8341 from Texas Instruments Inc., is used in the data acquisition system (DAS). The instrumentation system is calibrated through a Fluke 435. The DAS has a sampling frequency $f_s = 4$ kHz to obtain 120,000 samples of each phase of current and voltage during 30 seconds of the induction motor at the steady-state regime. The motor start-up is controlled by a relay to automate the test run. An FPGA-based board is used for controlling the data acquisition process. The acquired data are sent to personal computer (PC) to be processed afterwards.

4.2. Investigated faults

In this work three fault conditions are considered: MAL, UNB mass and BRB under three different frequency operation 3 Hz, 30 Hz and 60 Hz. The MAL condition was carried out by shifting forward the band in the alternator pulley, so that the transverse axes of rotation for the motor and its load were not aligned as show in Fig 4(a). The UNB mass was produced by attaching a bolt in an arm of the rotor pulley as show in Fig. 4(b). The BRB condition was artificially produced by drilling a 7.938mm diameter hole in a rotor bar without harming the shaft rotor. Fig. 4(c) shows the BRB condition.

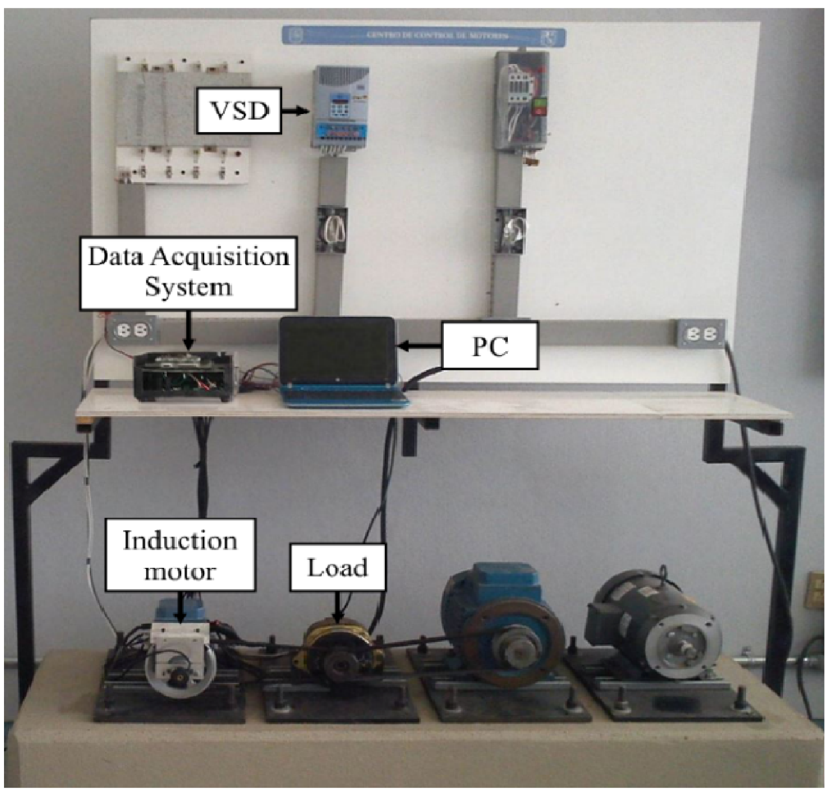
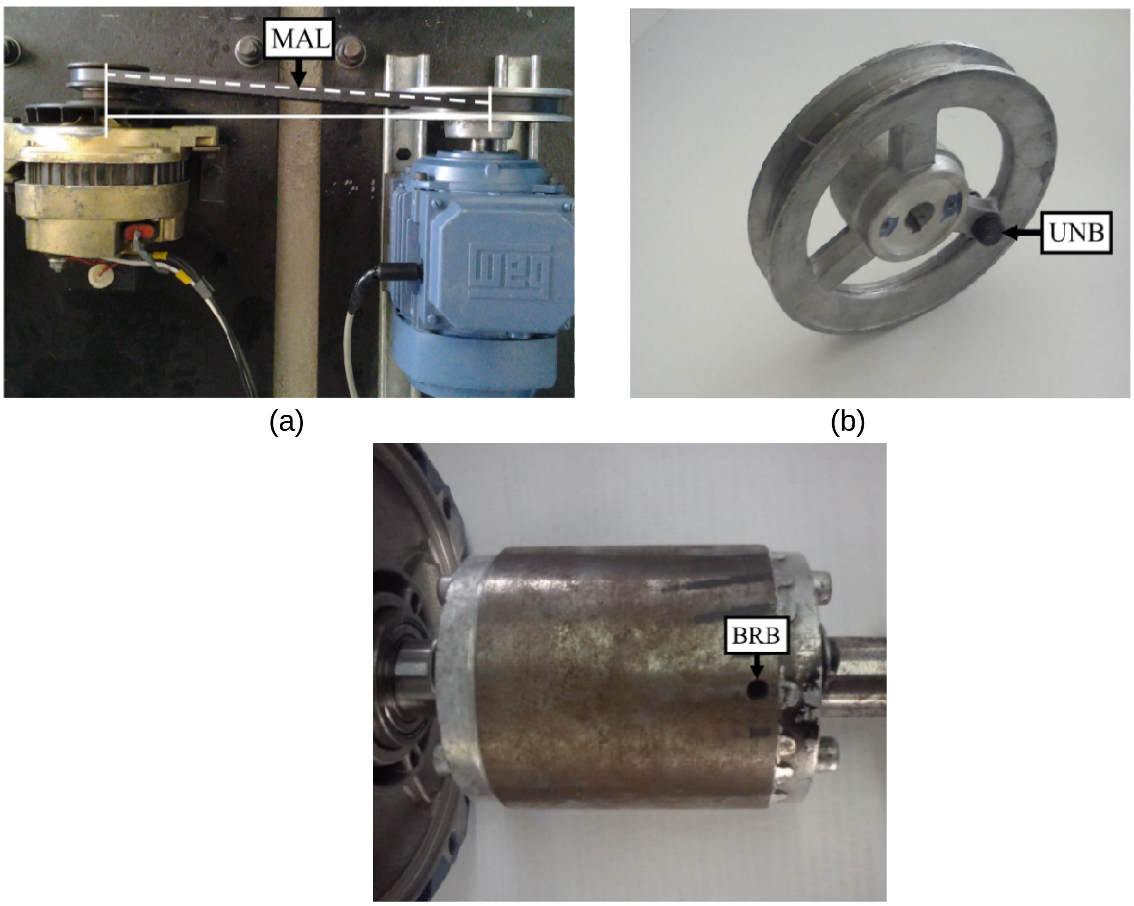


Fig. 3. Experimental Setup.

4.3. Fuzzy logic diagnostic system

The fuzzy logic diagnostic system is carried out through MATLAB for each frequency operation of the VSD. Four membership functions are proposed for the fundamental frequency amplitude and the spectral energy inputs as shown in Fig. 5, where the ranges of each function are estimated through the observed patterns in each frequency operation. A rule-base was developed to estimate the condition of the induction motor and five trials are acquired of each condition to validate the diagnostic.



(a) (b)

(c)

Fig. 4. (a) Misalignment. (b) Unbalance. (c) Broker rotor bar.

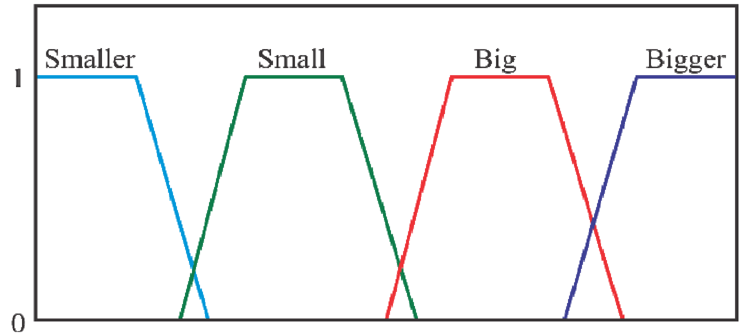


Fig. 5. Membership function proposed for the fundamental frequency amplitude and the spectral energy.

5. Results

5.1. Fault identification results

In Fig. 6 the obtained pattern for each operation frequency proposed (3 Hz, 30 Hz and 60 Hz) are presented, for this investigation the patters are: the fundamental frequency (FF) amplitude and the spectral energy. Then, the effectiveness of the fuzzy logic diagnostic systems for each selected frequency is shows in Table 1, which includes the identification of the HLT, MAL, UNB and BRB.

Induction motor condition	3Hz Effectiveness	30Hz Effectiveness	60Hz Effectiveness
HLT	100%	100%	100%
MAL	100%	100%	100%
UNB	100%	100%	100%
BRB	100%	100%	80%

Table 1. Effectiveness of the methodology for fault detection in induction motor.

6. Discussion

Three fault conditions are considered for this work (MAL, UNB and BRB) under three different frequency cases of the VSD. The operating frequencies are 3 Hz, 30 Hz and 60 Hz, the results of the methodology for each case are described below. The detection for healthy conditions have a 100% of effectiveness in all the operation frequencies proposed. Misalignment condition present an effectiveness of 100% in 3 Hz, 30 Hz and 60Hz. In the same way, in unbalanced condition a 100% of effectiveness was obtained in 3 Hz, 30 Hz and 60 Hz. Finally in broken rotor bar condition delivers an effectiveness of 100% for 3 Hz and 30Hz and 80% at 30Hz. The proposed methodology is a spectral analysis based in Park impedance, which is used for detection of faults in VSD-fed IM. This methodology is different from other works because it proposes to study the relationship of the Park's Impedance under fault conditions.

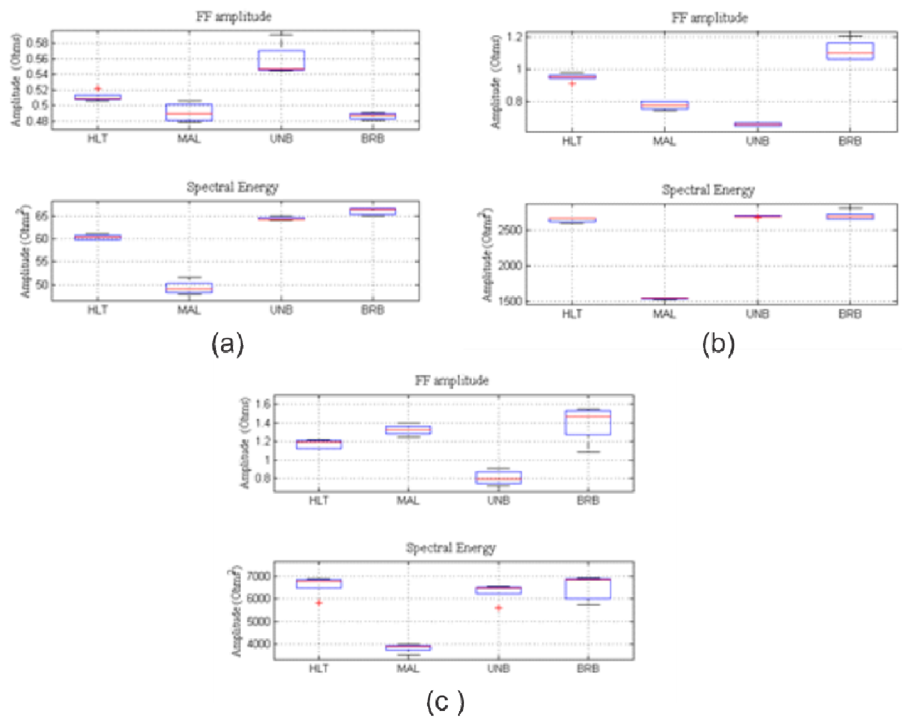


Fig. 6. Fundamental frequency amplitude and spectral energy in: (a) 3Hz, (b) 30Hz and (c) 60Hz.

7. Conclusions

In this work a methodology based on Park's impedance calculated by Park's current and voltage amplitude is performed. A spectral analysis is proposed to obtain the patterns used for diagnosis of faults in VSD-fed induction motors. Then, a fuzzy logic diagnostic system is used to classify the patterns and give a diagnosis about the condition of the induction in which excellent results are obtained in the proposed study cases. This methodology could be used with other techniques of signal processing to improve the patterns for fault classification or expand the analysis for other fault conditions.

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8. Biographies

Arturo Mejia-Barron received the M.S. degree in mechatronics from Autonomous University of Queretaro, Queretaro Mexico in 2015. Currently, he is a PhD. student of the Autonomous of Queretaro, Mexico. His interest fields includes mechatronics and hardware signal processing.

Armando G. Garcia-Ramirez received the B.E. degree from Mazatlan Institute of Technology, Mazatlan, Mexico, the M.E. degree (Hons.) from the University of Guanajuato, Salamanca, Mexico in 2011, and the PhD. degree (Hons.) from the Autonomous University of Queretaro, Queretaro, Mexico, in 2014 where did research work at the HSPdigital group. His interest fields includes embedded systems, signal processing and smart sensors for applications on mechatronics.

Roque A. Osornio-Rios (M'10) received the B.E. degree from the Instituto Tecnologico de Queretaro, Queretaro, Mexico, and the M.E. and the PhD degrees from the University of Queretaro, Queretaro, Mexico, in 2007. He is a National Researcher with CONACYT. He is currently Professor with the University of Queretaro. He was an Advisor of over 40 theses, and a coauthor of over 60 technical paper in international journals and conferences. His fields of interest include hardware signal processing and mechatronics. Dr. Osornio-Rios received the “2004 ADIAT National Award on Innovation” for his work in applied mechatronics.

Rene de J. Romero-Troncoso (M’07-SM’12) received the PhD. Degree in mechatronics from the Autonomous University of Queretaro, Queretaro, Mexico in 2004. He is a National Researcher level 2 with the Mexican Council of Science and Technology, CONACYT. He is currently a Head Professor with the University of Guanajuato and an Invited Researcher with the Autonomous University of Queretaro, Mexico. He has been and advisor for more than 200 theses, an author of two books on digital systems (in Spanish), and a coauthor of more than 100 technical papers published in international journals and conferences. His fields of interest include hardware signal processing and mechatronics. Dr. Romero-Troncoso was a recipient of the 2004 Asociacion Mexicana de Directivos de la Investigacion Aplicada y el Desarrollo Tecnologico Nacional Award on Innovation for his work in applied mechatronics, and the 2005. IEEE ReConFig Award for his work in digital systems.