Diagnosis of Rotor Failures Current Power Induction Motors by Spectral Analysis Methods

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Abstract: - Nowadays many tasks which a modern industry carry out, are performed by induction motors, becoming the core of most common industrial processes. The operators of induction motor drives are under continual pressure to reduce maintenance costs and present unscheduled downtimes which result in loss of production and financial income. Many operators now use online condition-based maintenance strategies in parallel with conventional planned maintenance. Motor current signature analysis (MCSA) is the online analysis of current to detect faults in a three-phase induction motor drive while it is still operational and in service. In industrialized countries between 40% and 50% of all energy produced is generated for consumption of these engines. As the market of these engines has grown and continuous and efficient monitoring has become indispensable, companies have to progressively invest on methods of preventive maintenance based on prediction of failures on operation programs. This type of maintenance, also known as condition-based maintenance (CBM) is an approach which changes the functioning condition and / or team performance when making decision as repairs or replacement. The goal of CBM is to minimize the total cost of inspections and repairs to collect and interpret data related to the operating condition of critical components of a computer continuously (online) or discontinuous (over time). This paper focuses only on fault detection by broken bars in squirrel cage induction motor and more specifically in the task of signal analysis and diagnosis, using LabVIEW software platform by a method which applies the Fourier Transform for spectral analysis of the feed stream.

Since our interest is focused on signal analysis, rather than on the acquisition of technical data, the choice of LabVIEW as a deployment platform which facilitates the acquisition and signal conditioning, was intentional to carry out tests with signals stored provided by Massey Technical Service Laboratory.

MCSA is presented as an excellent alternative online monitoring and non-invasive to diagnose many faults in induction motors becoming a tool to consider in predictive maintenance schemes.

LabVIEW allows a user- friendly implementation and facilitates the collection, processing, storage of data, facilitating the generation of reports and statistics.

Key-Words: - MCSA; Induction Motors; LabVIEW; broken bars

1 Introduction

Nowadays, as many of the tasks that a modern industry must carry out are performed by induction motors, induction motors have become the core of most common industrial processes.

In industrialized countries between 40% and 50% of all energy produced is used for these machines [1]. As the market for these engines has grown to have control and continuous and efficient monitoring has become indispensable, companies have to progressively invest on methods of preventive maintenance based on prediction of failures on operation programs. This type of maintenance, also known as condition-based maintenance (CBM) is an approach which changes the functioning condition and / or team performance when making decision as repair or replacement [2]. The goal of CBM is to minimize the total cost of inspections and repairs when collecting and interpreting data related to the operating condition of critical components of a computer, continuously (online) or discontinuous (over time). Thus the CBM reduces costs of inspection and repair by allowing the identification of those faults when they are close to occur. In this case, repairs are based on the degradation of equipment preventing costly repairs when they are either based on specific time intervals (preventive maintenance programmed) or emergency failures. CBM avoids excessive preventive technical activities and maximizes the service life of the components or equipment.

These new challenges highlight the importance of the development of new measurement strategies, acquisition and signal processing to evaluate the conditions of work equipment and the implementation of these maintenance methods. Failure statistics report that the engine components that tend to fail more often are: Stator (38%), Rotor (10%), Bearings (40%), Others (12%), [3]

Broken bars in the rotor represent 10% of the failures of a motor. Depending on its severity, failures can range from malfunction to an engine stop/halt, resulting in large financial losses for businesses due to unexpected changes in strikes production. There are various techniques and methodologies for detecting engine failure as for example, the impedance negative sequences, the analysis of the frequency spectrum, the vector Perk, the Hilbert transform, the analysis of the electrical signature, circuital engine analysis, vibration analysis among others [4]. Among the variables used to check the condition of a component or equipment are vibration, temperature, voltage, current, and oil level and insulation resistance.

This paper presents the analysis and implementation of an alternative method for the detection and diagnosis of fault rupture bars in the squirrel cage induction motors using spectral analysis of the feed stream known as MCSA (Motor Current Signature Analysis). The work aims to create a system of signal analysis and fault diagnosis algorithms based on spectral analysis of Corrientes (MCSA) easy to use and adaptable to signals with little prior conditioning.

This system has been processed by LabVIEW programming platform created by National Instrument. LabVIEW facilitates signal processing in the multiple ways which are used in the industry using the transducers that are in the market and that require little external adjustment. It also guarantees reliability, ease of deployment, a friendly-user interface, scalability and optimization of resources.

2 Methodology

Computer-aided maintenance is now a very important tool in detecting all kinds of faults in induction motors In this context, the MCSA is presented as an excellent alternative for online and non-invasive monitoring, used to diagnose faults such as broken bars in the rotor, abnormal levels of eccentricity of the air gap, short circuits in the stator windings in low voltage and other mechanical problems.

This paper focuses only on fault detection by broken bars in squirrel cage induction motor and promptly in the task of signal analysis and subsequent diagnosis, leaving aside the proper signal acquisition as shown in the Fig. 1.

Fig. 1 Global scheme for the use of MCSA

It is based on a study and implementation using LabVIEW software platform method based in applying the Fourier Transform for spectral analysis of the feed stream called induction motors MCSA.

2.1 MCSA foundation

For analysis of the effect of the broken bars on the supply current (stator current) of an induction motor we will use the general equation linking frequency (f), with the speed of the rotating field (n) and number of pole pairs of the machine (p), being this:

$$n = \frac{60 \times f}{p} \quad (1)$$

According to Theorem Ferraris, if made them a stator consisting of three coils of phase 120 ° in the circular space a system of three-phase currents balanced, the time lag is 120 °, a rotating magnetic field that surrounds is induced to rotor. This variable magnetic field will induce an electromotive force in the rotor according to the law of induction Faraday force through the same circulation of a current, which in their interaction with the field will generate a torque that will move the rotor.

Denoting by n_1 speed in $r.p.m$ synchronous rotation, ie the field created by the three-phase stator currents as a function of the frequency f_1 of these feed streams and the number of pole pairs p of the machine we have:

$$n_1 = \frac{60 \times f_1}{p} \quad (2)$$

Suppose the rotor rotating under load at a certain speed n in $r.p.m$ The speed difference between the field and the rotor $(n_1 - n)$ is the relative rotational speed with which the field lines intersect the rotor conductors and under this velocity difference are induced in the rotor winding $e.m.f.$ and currents of a frequency f_2 expressing in equation (1).

$$f_2 = \frac{p \times (n_1 - n)}{60} \quad (3)$$

The rotor polyphase currents in turn create a rotary field at a speed $(n_1 - n)$, in relation to the rotor in question and in the same direction as the stator field following the inductive sequence which it comes from. It is shown that relative to the stator, the rotor rotates at the speed field as:

$$n + (n_1 - n) = n_1 \quad (4)$$

That is, it rotates at the synchronous speed, regardless of the rotor's itself. Fields, stator and rotor remain stationary for one another and could be combined into a single rotating field that ultimately is left as resulting in the machine. It is important to note that in any healthy motor the speed of rotation of the rotor currents and fluxes behave or react this with respect to the stator $e.m.f.$ inducing therein the same frequency f_1 constant power line. The difference between the synchronous speed and the rotor speed is called slip speed $(n_1 - n)$, and is expressed per unit regarding n1 is represented as:

$$S = \frac{(n_1 - n)}{n_1} \quad (5)$$

According to equations (3) and (5) can be rewritten expression for the frequency associated with the sliding speed (f_2), corresponding to the frequency of the current and $e.m.f.$ induced in the rotor:

$$f_2 = \frac{S \times n_1 \times p}{60} \quad (6)$$

$$f_2 = S \times f_1 \quad (7)$$

If the engine has broken bars or unbalanced conditions, it creates asymmetry generating an additional magnetic field delay, which turns sliding speed, this is $-Sn1$ respect to the rotor [5]. With the presence of this field a stationary observer in the stator windings a rotating field will observe a resultant speed n_r defined:

$$n_r = n - S \times n_1 \quad (8)$$

It clearing of (5) the motor speed n in replacing (8) is obtained:

$$n_r = (n_1 - S\, n_1) - S\, n_1 == n_1 - 2\, S\, n_1 \quad (9)$$

Multiplying both sides of (9) by the number of pairs of poles p and considering the expression (1) is obtained:

$$n_r\, p = n_1\, p - 2\, S\, n_1\, p \quad (10)$$

$$f_r = f_1 - 2\, S\ f_1 = f_1\, (1 - 2S) \quad (11)$$

As the rotating magnetic field frequency f_r short the stator windings, is induced in them an $e.m.f.$ and hence a current with the same frequency of the rotating field, called f_{1r}, since it corresponds to the frequency of the current through the stator windings as well:

$$f_{1r} = f_1\, (1 - 2S) \quad (12)$$

This implies that under conditions of asymmetry resulting from broken bars in an induction motor, there is the presence of a sideband $2sf_1$ below the fundamental f_1.

The effect of broken bars also generates a cyclical variation in the current which results in an oscillatory torque and speed twice the slip frequency [5]. Consequently one sideband $2sf_1$ appears above the supply frequency f_1.

In conclusion, it has broken bars in the motor given as components result of currents that are induced in the stator coils and therefore are reflected in the feed stream to the motor frequencies given by (13) around the fundamental frequency f_1:

$$f_{1r} = f_1\, (1 \mp 2S) \quad (13)$$

It is important to note that it is normal for an induction motor which don´t have broken their bars present this asymmetry due, for example, an imbalance in the impedances of the windings, but these asymmetries are small comparable to those caused by the effect of the broken bars. That is why the presence of the sidebands around the fundamental frequency in an induction motor without failure is normal, but the amplitude of these sidebands are intensified with the broken bars and precisely is the amplitude ratio between the components critical current and these sidebands those considered for diagnosis.

Table I shows the criteria to diagnose broken bars in induction motors using MCSA [6].

Table 1
Fault diagnosis for MCSA

Difference between fundamental amplitude and sidebands	**Engine condition.**
54-60 dB	Excellent
48-54 dB	Good
42-48 dB	Probably have broken bars
36-42 dB	Broken bars
30-36 dB	Broken bars and probably another source of high resistance
<30 dB	Severe damage

2.2 Frequency analysis

Fourier transform FT is a mathematical tool used to convert a signal from the time domain to a signal in the frequency domain in order to observe the behavior of a function at a specific time.

If it has a signal defined by a function periodic f in the spectrum of frequency discrete, and if is considered a new function g no periodic defined in $[-\infty,\infty]$, and such that $f(t) = g(t)$ in the interval $[-\frac{1}{2}T, \frac{1}{2}T]$. New non-periodic function that results from f is:

$$g(t) = \begin{cases} f(t-nT) & |t| > \frac{1}{2}(2n-1)T \\ f(t) & |t| < \frac{1}{2}T \\ f(t-nT) & |t| < \frac{1}{2}(2n+1)T \end{cases}$$

The function f Fourier integral representation is given by the equation expression (14) is:

$$f(t) = \int_{-\infty}^{\infty}\left[\frac{1}{2\pi}e^{jw}\int_{-\infty}^{\infty}f(\tau)e^{-jw\tau}d\tau\right]d\omega \qquad (14)$$

Where j is the imaginary unit, and it must meet two conditions sufficient for the existence of equation (14), which is a corrected form of the equation of Dirichlet, and posed as f must:

- be absolutely integrable in $[-\infty,\infty]$, or $\int_{-\infty}^{\infty}|f(t)|\,dt$ is convergent.
- have a number finite of maximum and minimum and be continuous by sections.

In addition, equation (14), can be written:

$$F(j\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-jwt}\, dt \qquad (15)$$

To the expression defined in (15), it is called Fourier transform of f, and provides a representation in the domain of the frequency of a function not periodic f [7].

FT has been approached from the format, closer to their use in methods and computational algorithms discrete signal; whose formulation is presented in equation (16).

$$F\left(\frac{n}{NT}\right) = \frac{1}{N}\sum_{k=0}^{N-1} m(kT)e^{-j\frac{2\pi nk}{N}} \qquad (16)$$

Where $n = 0,1,2\ldots(N-1)$ and N is the number of samples of the window to be analyzed, T is the sampling period (inverse of the sampling frequency), n is the index of the frequency whose value we want to obtain and $m(kT)$, indicates a sample taken at instant kT (k-th sample) in the area where the images of non-periodic function coincides with the image of the periodic function.

The foundation on which the FT is based lies in the comparison of several sine waves and simple cosine with the complex signal analyzed, the more matches a simple wave with the complex signal, the more important is its frequency in determining the original signal. At this point it should be noted that when we analyze a signal frequencies, the information we consider relevant are the frequencies of simple signals with greater amplitude obtained from the decomposition of the original signal [6].

Implement DFT Discrete Fourier transformation on N samples requires approximately N^2 complex operations in a time consuming process. For this, the algorithm computationally Fast Fourier Transform (FFT) allowing calculation of DFT in fewer operations, approximately $N\,log_2(N)$ is applied (If N is a power of 2) and therefore operations realize much faster [8] [9].

2.3 Frequency analysis implemented with LabVIEW

LabVIEW is a graphical programming software created by National Instruments and it has integrated functions for data acquisition, instrument control, measurement analysis and data presentation. The main feature of this software is its ease of use, since it has an extensive library of powerful tools to create relatively complex applications without writing code lines of text. Programs developed with LabVIEW are called Virtual Instruments (VIs) which can be used in turn as building blocks for more complex programs. Each VI consists of two parts: the front panel, which is the interface used to interact with the user when the program is running and the block diagram, which is the program itself and where the icons are placed that interconnect with each other and perform the functions established [10].

Power Expectrum.vi the *FFT* Power Measurements Waveform tool corresponding to the library Signal Processing shown in Fig. 2 was used to implement the *FFT* algorithm.

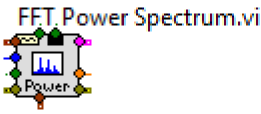

Fig. 2 *FFT* Power Expectrum.vi

In Fig. 3 and Fig. 4 the front panel of the system and part of the block diagram of the main program where as mentioned above programming is developed and is invisible to the system operator, as this only interacts with the front panel where shown operates controls and receives information.

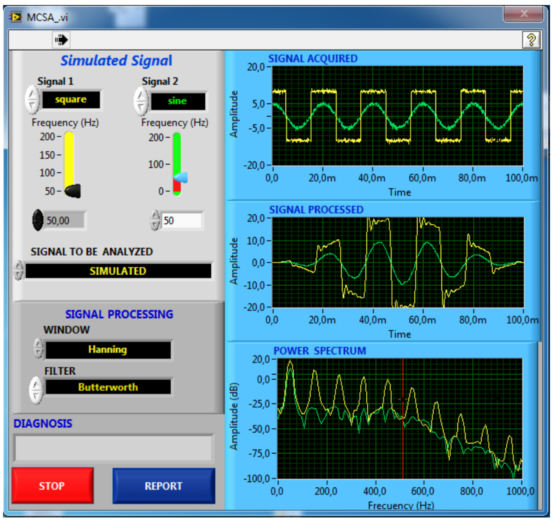

Fig. 3 Front panel

Through the control call *signal to be analyzed* it can choose the signal source to study, with the options: *Simulated* corresponding to a signal generated by the same system through appropriate controls, *Stored in disco* corresponding to a signal that has been taken *offline* and stored in a file, and finally *Acquired from*, or *Acquired from abroad* which refers to a signal that is *online* by an acquiring data plate and can be processed at the same time Fig. 5 describes these options.

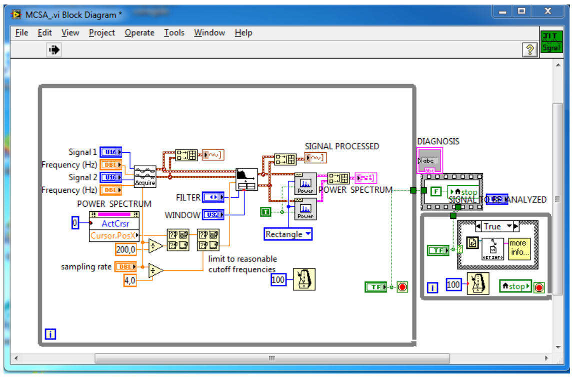

Fig. 4 Block diagram

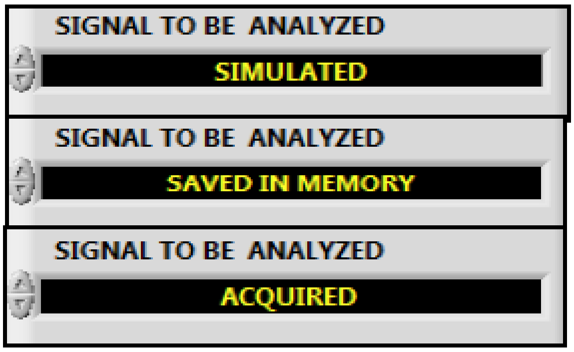

Fig. 5 Options control *signal to be analyzed*

Since our interest is focused on signal analysis, rather than technical data acquisition and considering choosing LabVIEW as a deployment platform, the acquisition and signal conditioning, our tests were carried out with signs stored on disk. Note that the system is able to process signals from the outside once it has the corresponding procuring plate.

3 Analysis and discussion

The vibrations in a machinery are directly related with the useful life by two ways: a low level of vibrations is an indication that the machine works correctly during a long period of time, while an increase in the level of vibrations report that the machine is heading towards some type of failure, since about 90% of machinery failures are preceded by a change in the vibration feature.

The results are showed after test two induction motors with squirrel cage, one with healthy rotor and the other with broken bars. Table II shows the data of the engines tested which have been provided by Massey Technical Service Laboratories.

Table II
Engines tested data.

Motor	healthy	damaged
V_{nom}	220/380 V	220 V
I_{nom}	11/6,5 A	16 A
Frequency	60 Hz	60 Hz
N° poles	2	2
Power	4 *CV*	3 *CV*
Speed test	3457 rpm	3480 rpm

Fig. 6 and Fig. 7 shows the results of testing a damaged motor rotor

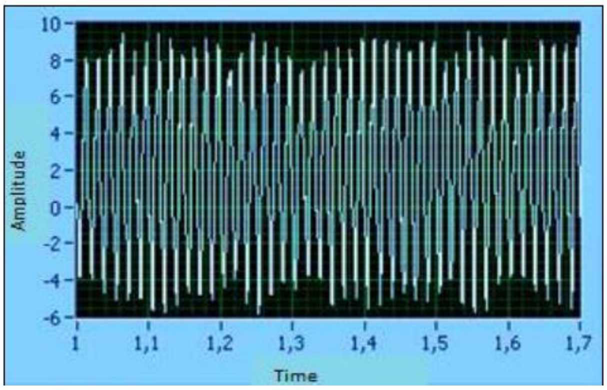

Fig. 6 Time response of the motor current damaged

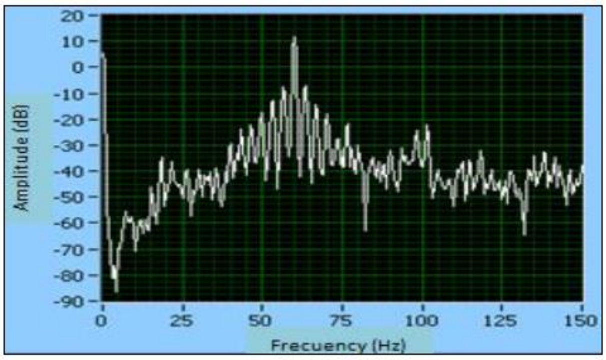

Fig. 7 Frequency spectrum of the motor current damaged

Fig. 8 shows the report frequency response in the range of interest and diagnosis of the engine as the view expressed in Table I. They can be observed current frequencies peaks $60\,Hz$, $63{,}33\,Hz$, and $56{,}67\,Hz$, corresponding to the fundamental and the sidebands coincide with those expressed in equation (13). The difference between the highest peaks of the sidebands and the fundamental $19{,}22\,db$, which means that the engine is in severe damage to the rotor.

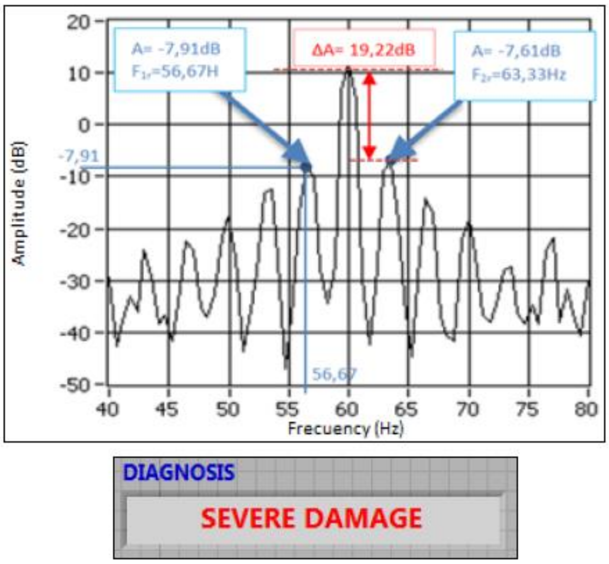

Fig. 8. Motor test report damaged

Failures should be detected when they still do not significantly affect the machine so as to perform in this way the corresponding preventive maintenance. Otherwise, the fault would affect significantly the operation of the engine at the moment of its identification, resorting to the model of maintenance corrective.

Fig. 9 and Fig. 10 show the results of testing a healthy motor rotor.

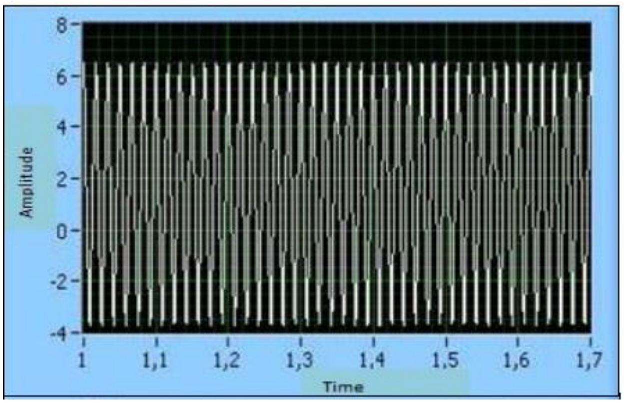

Fig. 9 Time response of the current healthy motor

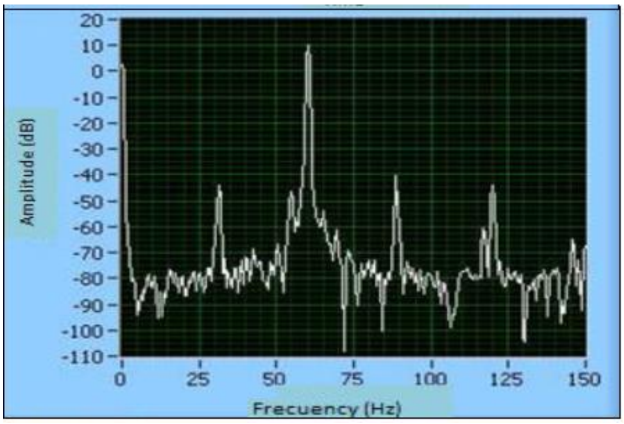

Fig. 10 Frequency spectrum of the current healthy motor

Fig. 11 corresponds to the report of the frequency response in the range of interest and diagnosis of the engine as the view expressed in table I.

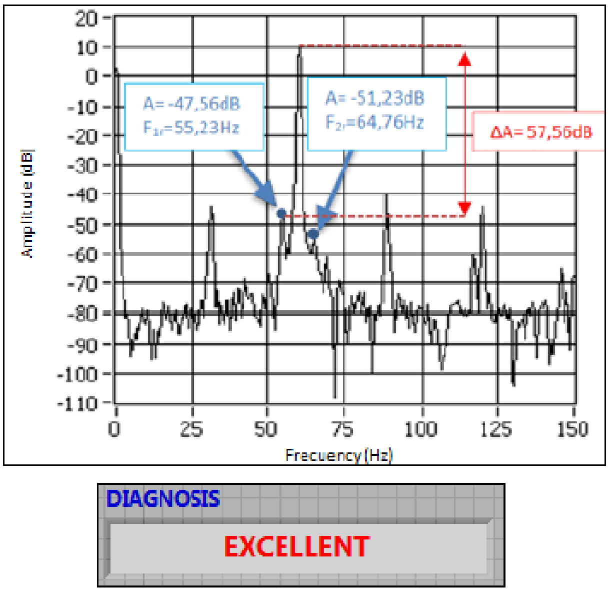

Fig. 11 Test report for healthy motor

Troubleshooting is facilitated with increasing engine load, since the higher the load, the lower the speed, the greater the slip, resulting in greater distance between the fundamental harmonic and sideband and therefore easier to distinguish. It is recommended that the fault diagnosis is made with the engine close to the rated load.

The amplitude of the side harmonics is proportional to the degree of fault of cage motor, so the difference in dB between the magnitudes of fundamental and harmonics decrease as more broken rotor bars exist in the cage.

Broken rotor bars on the motor creates two lateral bands on current's frequency spectrum, located on doubles frequencies of the frequency slide ($2sf_1$) among fundamental frecuency f_1

Analyzing voltage signals in addition to the current, the method can diagnose failures both electrical, and mechanical among which are: broken rotor bars breaking rings rotor shorts the stator coils, rotor eccentricity, bearing failures, among other. The possibility along with the implementation of the signal acquisition stage is presented on the horizon as a continuation of this work in the future.

MCSA requires a frequency analysis, and having digitalized and filtered signals, it must calculate a FDT (Fourier discrete transform), with the purpose to optimize the computational process, it uses the FFT (Fourier fast transform) which is an algorithm than allow to calculate the FDT faster.

The Hanning window, generally, is the better way that fit frequency analysis system, like the implemented in the project, due that the system has lineal characteristics and break-off suppressions.

4 Conclusions

The Motor Current Signal Analysis (MCSA) is one of the most popular used method because for the following reasons. Firstly, it is noninvasive. The stator current can be detected from the terminals without breaking off drive operating. Secondly, it can be measured online therefore makes online detection possible. Thirdly, most of the mechanical and electrical faults can be detected by this method. MCSA is presented as an excellent alternative online monitoring to diagnose a lot of faults in induction motors becoming a tool to consider in predictive maintenance schemes. It is necessary to stress that for the proper implementation of the MCSA as predictive maintenance tool, is necessary condition the prior knowledge of the state of operation of the engine and its evolution over time. Therefore it is advisable to perform tests on the engine periodically in order to determine the evolution of the motor.

This technique can be fairly simply, or complicated, depending on the system available for data collection and evaluation. MCSA technology can be used in conjunction with other technologies, such as motor circuit analysis, in order to provide a complete overview of motor system health.

Using LabVIEW technology allows the implementation to be user friendly and facilitate the collection, processing, data storage and the ability to generate reports and statistics in a simple way.

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