Continuous health status detection of a motor

1. ***Excellence***

   1.1. ***State of art, knowledge needs and projects objectives:***

Nowadays, timely maintenance of electric motors is vital to keep up the complex processes of industrial production. Causes of motor failures are different: bearing faults, insulation faults, and rotor faults, misalignments etc. Early detection of these faults allows replacement of the components, rather than replacement of the motor.

Determine the continuous health of a motor can be useful to predict a failure and to enable some procedures to put the motor into safety condition. This can also help the engineer to be aware of the type of the failure.

Actually most technique use contact sensor; the most popular for the detection of faults in induction motors with contact sensors are: the MCSA (motor current signature analysis) and the analysis of vibration signals. The MCSA technique involves the analysis of stator current signals collected with a current clamp or an ammeter. It is based on the recognition that an electric motor (ac or dc) driving a mechanical load acts as an efficient and permanently available transducer by sensing mechanical load variations and converting them into variations in the induced current generated in the motor windings. These motor current variations are carried by the electrical cables processes as desired. Motor current signatures, obtained in both time and over time to provide early indication of degradation. The signal acquisition can be carried out during either a start-up transient or a steady-state regime of the induction motor. For signals acquired during a steady state, it is expected that the frequency content remains time invariant, and the analysis is performed with methods that provide efficient frequency decomposition with good tolerance to low signal-to-noise ratio. The most common technique in the analysis of stationary signal is the Fourier transform. However it has the disadvantage of a limited frequency resolution, the spectral leakage, and a low noise tolerance. If the motor operates in non-steady regime, several processing methods have been proposed: the signal could be analysed by time-frequency decomposition method such as the short time Fourier transform, the discrete wavelet transform, the continuous wavelet transform etc . The combined use of some this technique with an artificial intelligence helps to determine components or signatures that are present in the signals for identifying faults and their severity [1].

In order to diagnose motor faults, MCSA uses the current spectra, which contains potential information of motor faults. Therefore, it is important that abnormal harmonic frequencies are independent of the types of drive-systems or control techniques. Because of this property, MCSA is more useful than any other online motor diagnosis techniques.

Each fault is related to a precise harmonic in the current spectra; for example, a bearing failure cause the variation of air-gap length when a rotor turns. Since this variation comes from the defective structure of a ball bearing, the abnormal harmonic frequencies of a ball bearing can be derived from the bearing model [2]. The related frequency is:

$$f_{bearing} = f_0 \pm n_b f_{i,0}$$

$$f_{i,O} = \frac{n}{2}(1-s)f_0\left\{1 \pm \frac{\mathrm{BD}}{\mathrm{PD}}\cos\beta\right\}$$

Where n_b is the number of balls, PD is the bearing-pitch diameter, BD is the ball diameter, β is the contact angle of crack on races, and n is the positive integer, f_0 is the electrical supply frequency, s is the per-unit slip respectively. However, bearing parameters PD, BD, and β, cannot be easily detected; the manufacturer should supply that geometries in the datasheets. Also an misaligned shaft, due to an unbalanced load or a worn bearing, can cause an air-gap eccentricity in the motor. The air-gap eccentricity includes static and dynamic eccentricity; the last one appears when the rotor centre is not located at the rotation centre.

It has been shown that both static and dynamic eccentricity give rise to abnormal harmonic frequencies in a stator current given by [3]:

$$f_{\mathrm{ecc}} = \left\{ (R \pm n_d) \left(\frac{1-s}{p} \right) \pm n_{\omega s} \right\} f_0$$

where R is the number of rotor slots, $n_d = \pm 1$ is the eccentricity-order number, and $n_{\omega s} = 1,3,5, \ldots$,the stator MMF-harmonic rank, respectively.

Another way to determine the health status of a motor is the vibration analysis. It is based on the signal coming from accelerometer/vibrometers positioned on the crankshaft; 3-axis MEMS accelerometers are frequently used due to its ability to measure vibration at very low frequency, around 0Hz. Through the spectral analysis of the shaft-vibration is possible to determine the presence of fault inside the motor. The bearing fault related vibration frequencies are easily calculated with known bearing geometry and rotor speed [4]. The vibration frequencies show up also in the current spectrum as the modulation frequencies, therefore it is possible to provide continuous monitoring using motor current data, as in MCSA analysis, instead using crankshaft's vibration data.

Bearing faults such as outer race, inner race, ball defect, and train defect cause machine vibration and it results in air-gap eccentricity. These defects have vibration frequency components, f_v, that are characteristic of each defect type. The outer race defect frequency is:

$$f_{\mathrm{oD}} = \frac{n}{2} f_{rm} \left(1 - \frac{\mathrm{BD}}{\mathrm{PD}} \cos \phi \right).$$

where f_{rm} is the rotor speed in revolutions per minute.

The inner race defect frequency is:

$$f_{\mathrm{ID}} = \frac{n}{2} f_{rm} \left(1 + \frac{\mathrm{BD}}{\mathrm{PD}} \cos \phi \right).$$

Ball defective frequency is given by:

$$f_{\mathrm{BD}} = \frac{\mathrm{PD}}{2\mathrm{BD}} f_{rm} \left(1 - \left(\frac{\mathrm{BD}}{\mathrm{PD}} \right)^2 \cos^2 \phi \right).$$

Cage defect frequency, caused by irregularity in the train, is given by:

$$f_{\mathrm{CD}} = \frac{1}{2} f_{rm} \left(1 - \frac{\mathrm{BD}}{\mathrm{PD}} \cos \phi \right).$$

There is a relationship between the characteristic frequency of a fault in the current spectra and the vibration spectra. The characteristic current frequencies, f_{CF}, due to bearing characteristic vibration frequencies are calculate by

$$f_{\mathrm{CF}} = |f_e \pm m f_v|.$$

where f_v is the vibration frequency components of the fault and f_e is the power system frequency.

The others parameters are relate to the geometry of ball bearing and is shown in the figure 1 below:

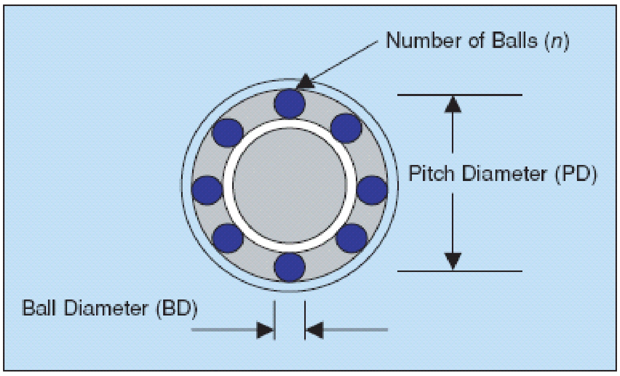


Figure 1 credits to [4]

All these techniques for fault diagnosis have advantages and disadvantages.
The MCSA technique has the advantages of being non-invasive, easy and cheap to implement, providing good results in fault diagnosis; however, under certain conditions its application is not sensitive enough because it has a low signal-to-noise ratio. In the other hand, vibration analysis has the advantage that its results are independent of the type of motor power supply, high reliability, low power consumption, low cost and yields good results, but its implementation requires using accelerometers as the basic sensors that must be placed near or on the motor, which sometimes is difficult to achieve.

To partially solve the problem of using only contact sensors, Paulo and Daniel [5] proposed to detect fault through sound and vibration signals; in fact the sound is a physical phenomenon that provides information about the behaviour of a system and can be used as a parameter for determining the condition thereof. The acoustic sound waves contain information about the health status of the machine because sound is produced by mechanical vibrations. The electric motor is not an exception, and the vibrations generated by defects in bearings, mechanical unbalances and broken rotor bars produce sounds with characteristic frequencies associated with each fault.
However the downside of sound signal analysis is its sensitivity to external noise , which should be avoided whenever possible; this limits enormously the application of this technique. The diagnosis through the analysis of acoustic sound signal is a first non-invasive method using non-contact sensor, a microphone in this case, to check the motor's status.

Vibrations are a key factor to determine the health of a motor. This project wants to determine the amplitude of the vibration of the shaft using a Lidar and analysing the presence of harmonics inside of the displacement is possible to retrace some known fault. McFadden [6] and M. J. Devaney [4] describe that every superficial defect of the mechanical components is related to a specific frequency that is proportional to the speed of the shaft, as reported before. But also other defects, specific for induction motor (most common type of motor in the industry), have typical harmonics in the spectrum.

1.2. *Research question and hypothesis, theoretical approach and methodology*

The development of the project is based on different research questions. Using a Lidar, it is necessary to determine the correct distance between the sensor and the shaft. Also, how it is possible to determine the amplitude of the displacement of the shaft while the motor is working. The presence of a load attached to the shaft can disturb the readings, if the load is unbalanced.

In a system with multiple-fault conditions present, such as broken rotor bars (BRBs), unbalance (UNB), and bearing defects (BDs), it is important to distinguish between the faulty conditions, [7]. When multiple faults exist, vibration and current are excited by several fault-related frequencies combined with each other, linearly or nonlinearly. Since multiple-fault situations may occur in the induction motor, a wrong conclusion may be drawn in the diagnosis based on the partial fault signature. Therefore, multiple-fault diagnosis is still a big challenge in the research of monitoring and maintenance of induction motors. This project considers that only one fault can occur in the motor for each run-time. Otherwise, as described in [7], the analysis of the vibration's spectrum become more complex; the main scope is to use a non-contact sensor to determine the health status, so the project is mainly focused on the acquisition part of the entire system and the signal processing.

The project is articulated in different phases: at first the Lidar must be properly adjusted and sets all its parameters; particularly its important to set the range resolution of the lidar because it has to measure vibration of 0.01mm at least. For this reason its better to use lidar than a radar.

Often retro-reflective tape is applied to the target shaft to facilitate use of a low-powered laser and improve the measuring quality. The lidar is mounted perpendicular to the shaft however any inclination can modify the measure. This happen because, the beat frequency, f_d is directly proportional to the shaft speed (ω) and is independent of any solid body motion of the shaft. If the plane of the laser beams is not perpendicular to the shaft axis, then f_d is also a function of $cos\ \theta$, where θ is the angle between the plane of the laser beams and the plane perpendicular to the axis of shaft rotation.

The voltage data coming from the lidar is captured and appropriately filtered to reduce the noise and processed doing the Fourier transform of the signal, so it is possible to determine the speed and the displacement of the vibration. It can be used banks of filter, each for the frequency window in which an harmonic can appear. However the FFT gives only frequency information; from a frequency spectrum is impossible to determine at what time the fault occur. For this reason, the system proceed with the wavelet transform that contains both temporal and spectral information. After that the system determine the spectral information, it compare each harmonics with a table that contains the characteristic frequency of the most common fault which can occur in the motor; if it will find a matching frequency and that harmonics as a relevant amplitude then is able to inform the user about the fault. To validate this process, every characteristic frequency of the table will be checked injecting in the system a known fault. For example, drilling an hole in the bearings cause the presence of a specific harmonic in the spectrum calculated from an equation. Running the system, with the hole in the bearings, it appears a relevant harmonic in the spectrum. So, we will compare the experimental frequency with the theoretical one to validate the equation.

1.3. Novelty and Ambition:

A lidar is a non-contact sensor, that can be used to determine the speed of the motor, so to apply this technique the motor must not but modified. In fact, the actual technique requires to put a sensor on the motor, this could be very difficult if the motor is in hostile and uncomfortable places like for example on the wind turbine. The project wants to present how to determine the amplitude of displacement and speed of a motors shaft.

2. Impact

2.1. Potential for academic impact of the research project

The output of this project could raise new academic challenges. Determinate the continuous health status of a motor can helps to develop different type of predictive maintenance. For example, is possible to determine if some components inside of the motor are going to fault and schedule a maintenance before the broke ; this helps reducing drastically the downtime of a machine.

2.2. Potential for societal impact of the research project

The project's target audience is composed by all researcher whose need to implement different types of fault detection in motors, to improve their predictive maintenance scheme. But also, for who want to improve non-contact control of a motor, because it is allocated in a hostile environment for classic contact sensors.

2.3. Measurer for communication and exploitation

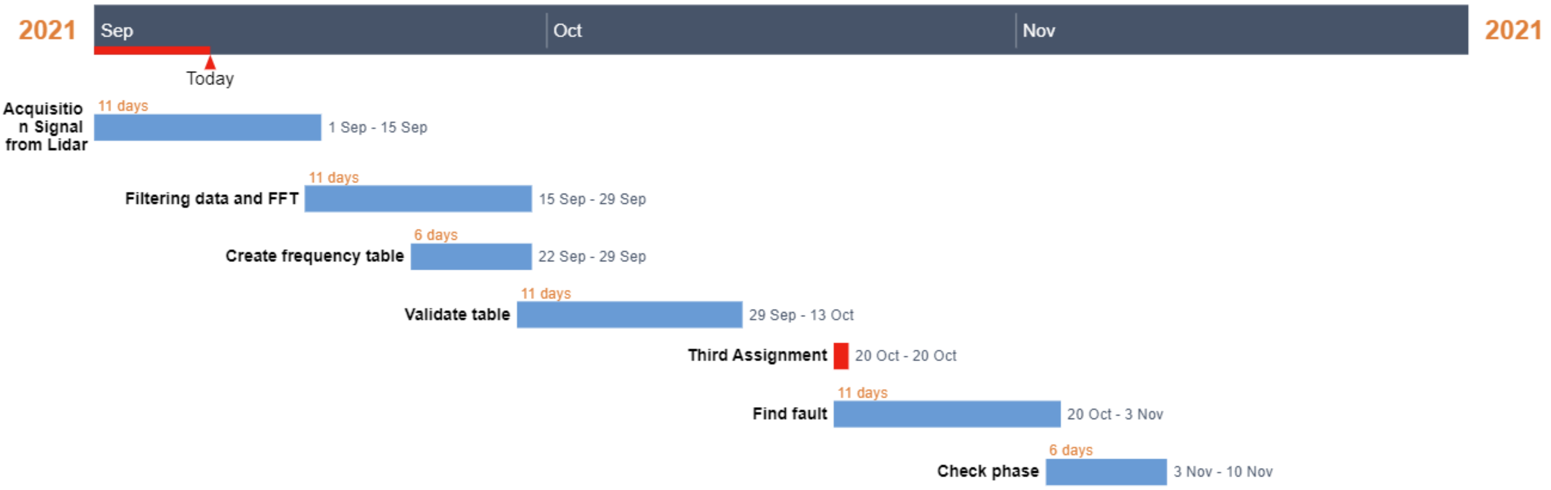
This work will be published in specialized magazines because can be useful for who wants to improve this project including, for example the ability to recognized the precise fault.

3. Implementation

3.1. Project organisation and management

The project will be divided in different tasks: at the beginning we proceed with the setting of the Lidar and how to acquire its data. After the sensing part, we continue with the implementation of the code that must filter correctly the signal and then we execute the Fourier transform of the signal and determine the speed of the vibration and the displacement of it. In order to obtain the temporal information regarding at what time a fault occur, we implement also the wavelet transformation of the signal. The system need to find in the signal spectrum the harmonics related to fault, for this reason we create a table of relevant frequency for each fault. This table will be validated experimentally. In the end, everything must be fused in a project and test the project in laboratory.

The workflow is described in the Gantt chart below:


2021
Sep
Oct
Nov
2021
Today
Acquisition Signal from Lidar
11 days
1 Sep - 15 Sep
11 days
Filtering data and FFT
15 Sep - 29 Sep
6 days
Create frequency table
22 Sep - 29 Sep
11 days
Validate table
29 Sep - 13 Oct
Third Assignment
20 Oct - 20 Oct
11 days
Find fault
20 Oct - 3 Nov
6 days
Check phase
3 Nov - 10 Nov

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