Summary

Electrical machines maintenance is crucial to guarantee the continuity of industrial process. In recent years, extensive research on the diagnosis of rotating electrical machines has been focused in obtaining discriminatory features from the measurable quantities (mechanical and electrical) of the motors and generators installed in the traditional industry, and also in emerging fields such as wind energy, electric traction, etc. The main goal of the fault diagnosis developed techniques is to determine the condition of the motor by identifying the fault and quantifying its severity in order to develop preventive and corrective maintenance to reduce the economic impact of the damage. Recently, and in order to detect the relevant features produced by failures in the electrical machine, one of the most common quantity being analysed, along with the electrical machine vibration, has been the stator phase current. In addition, the instantaneous value of the stator phase current and its time evolution are often available on the electrical installations cabinets, or even in electronically control equipment and, otherwise, can be measured easily it by means of a non-invasive clamp meter.

In the scientific-technical literature, one can find different signal processing techniques that allow discriminating the faulty or healthy condition of the electrical machine. Usually, each of these techniques or methods is used for one specific magnitude, or for particular working conditions, or for one kind of failure, etc... Therefore, they often have inherent limitations has associated to their different characteristic features and require an expert to recognize the condition of the motor considering the technique used and the fault type.

It is therefore essential to automate this expert task by using artificial intelligence and learning-machine techniques based on automatic classifiers. It is also a priority to research and to develop new detection systems more accurate than the previous ones. Complex systems based on expert systems capable to learn identifying failures (systems such as multidimensional classification systems or expert systems based on simulating a "brain" using neural networks) are used to improve the classification of faults.

My background includes the fields from the industrial automation to artificial intelligence and experts systems and is used to develop an automatic “supra-system” capable to generate optimal fault diagnosis systems. These optimal systems are adaptable to the type of electrical machine applied. This "supra-system" can generate new optimal fault diagnosis systems automatically when applied to new types of electrical machines. Generated optimal diagnostic systems maximize the accuracy in failure detection and minimize the computation costs as a secondary objective. In addition, from the relevant features obtained from the detection failures, expert classification systems have been adapted to the relevant features in order to obtain the optimal diagnostic system for each type of fault.

The proposed "supra-system" is able to generate the optimal diagnostic system for the fault detection induction motors. This optimal diagnostic system is composed by a diagnostic technique and a classifier expert system. This has been achieved following these steps:

- **Data Acquisition**.

An experimental test-bed is used with two motors mechanically coupled directly. One of them, the test case, is an asynchronous induction machine (healthy or faulty) and the other is a synchronous permanent magnet motor, which acts as a load torque on the system. Different tests have been performed, and the three phase stator currents have been measured along with the motor, at different conditions:

  - constant load torque and speed of the motor.
  - constant load torque and variable speed motor.
  - variable load torque and constant speed motor.

- variable load torque and speed motor.

All tests were repeated in order to check the proper condition of each test. Besides, different tests from the four categories above, with different motor speeds and load torque levels have been performed. In total, 735 data sets were obtained and fed to the following diagnosis techniques to be analysed with the “supra-system”.

- **Diagnosis techniques/methods applied.**

Different diagnosis techniques/methods have been used depending on the test conditions in order to extract relevant diagnosis features. Moreover, two novel techniques have been developed and included within this thesis frame: the use of the prolate window and the use of the short frequency Fourier transform.

The signals used for diagnosis are:

- The stator phase current.
- The stator phase current multiplied by a Hanning window (Hann).

The techniques used for the steady-state regime are:

- Signal analysis.
- Analysis of the analytical signal modulus (Hilbert transform).
- Analysis of Cepstrum transform.
- Analysis of Park transform modulus.
- Harmonic order tracking analysis (HOTA).

The signal is analysed in the frequency domain by:

- Analysis of the Fourier transform.
- Analysis of Welch method.

In conclusion, for the steady-state regime 20 different diagnostic methods have been explored, resulting from the combination of the possibilities described above.

The techniques used for the transient regime are:

- Harmonic order tracking analysis (HOTA) using the Short-Time Fourier Transform (STFT) with Gaussian window.
- Harmonic order tracking analysis (HOTA) using the Short-Time Fourier Transform (STFT) with Prolate window ***(This window is a contribution of this thesis)***.
- Harmonic order tracking analysis (HOTA) using the Short-Frequency Fourier Transform (SFFT) with Gaussian window ***(This technique is a contribution of this thesis, and it is modified from the STFT).***
- Harmonic order tracking analysis (HOTA) using the Short-Frequency Fourier Transform (SFFT) with Prolate window.

Besides, a set of improvements over the original HOTA algorithm recently presented in the technical literature have been implemented to the different HOTA variants above. These improvements reduce the computation time and the storage memory requirements, which is essential in the design of an expert system. The improvements proposed in this thesis are:

- ***A new band-pass filtering stage to attenuate high frequencies.***
- ***The minimization of the edge effect.***
- ***A new faster algorithm for the optimum setting of the filter window.***

In conclusion, for the transient regime 4 different diagnostic methods are explored.

- **Extraction of relevant features.**

For each of the techniques used, the relevant features are obtained, in this case a couple for each motor test or measured current. Thus, a matrix is obtained with as many feature vectors column as the number of diagnostic techniques used (20 in steady-state and 4 in transient) and as many rows as the number of tests used in this thesis (over 700 tests).

- **Obtaining the classifiers.**

For each of the feature vectors obtained with each of the diagnostic techniques used, different classifiers are generated based on the following types:

  - Artificial neural networks with one hidden layer.
  - Artificial neural networks with two hidden layers.
  - Support Vector Machine with polynomial kernel function.
  - Support Vector Machine with Gaussian kernel function.

The optimization algorithm (validation system) is used to generate different classifiers of each type of classifier; a multitude of classifiers is generated with different coefficients to obtain the optimal classifier.

- **Selecting the optimal expert system.**

In the final step, the results are analysed and the selection of the optimal system composed by the best classifier and the best diagnosis technique. The "supra-system" obtained has the following advantages:

1. It achieves a final optimal diagnostic system.
2. It produces several local optimal diagnostic systems (for the same technique and expert system) taking into account the training time and the estimated diagnosis time. Thus, the "supra-system" not only provides a final optimal solution, but also allows the operator to choose one of the generated alternative local optimal solutions in case calculation time restrictions must be taken into account
3. It is completely autonomous. The operator must provide the signals from a specific motor type and the "supra-system" generates the optimal diagnostic system without operator intervention.
4. It is adaptable to the induction motor type, as it can generate an optimal diagnostic system specific for each type of motor.

The thesis has been structured into the following chapters:

- Chapter 1 is a brief introduction that it used as starting point and the main objectives of this thesis are presented.
- Chapter 2 is a scientific-technical review on the faults in rotating electrical machines, as well as on the main signal processing techniques applied to fault diagnosis. Finally, the main artificial intelligence systems are reviewed.
- Chapter 3 shows a description of the classification systems to be used in this thesis and its features.
- In chapter 4 the test bed and the tests are described as well as the management of the acquired signals.

- Chapter 5 describes the relevant features in the steady-state regime of the electrical machine as well as the development of the system to be applied to this work regime and the results obtained.
- Chapter 6 describes the relevant features in the transient regime of the electrical machine as well as the development of the system to be applied to this work regime and the results obtained.
- Finally, in Chapter 7 the main conclusions and contributions of this thesis in the field of diagnosis electrical machines are presented. Also the future research topics that should be addressed in the near future are shown.