Henao, H.; Capolino, G.; Fernández-Cabanas, M.; Filippetti, F.; Bruzzese, C.; Strangas, E.; Pusca, R.... (2014). Trends in Fault Diagnosis for Electrical Machines. IEEE Industrial Electronics Magazine. 8(2):31-42. doi:10.1109/MIE.2013.2287651

Trends in Fault Diagnosis for Electrical Machines

Journal:	*Industrial Electronics Magazine*
Manuscript ID:	F-0048-IEM-07-2013
mstype:	Main Feature
Date Submitted by the Author:	08-Jul-2013
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Specialty Area:	Motor Drives and Electrical Machines, Electrical Machines < Motor Drives and Electrical Machines, Fault detection, diagnostics and prognostics < Machine and Drive Integrity < Motor Drives and Electrical Machines

Trends in Fault Diagnosis for Electrical Machines

1. Introduction

Fault diagnosis of rotating electrical machines has received an intense research interest for the last thirty years. Reducing maintenance costs and preventing unscheduled downtimes, which result in losses of production and financial incomes, are the priorities of electrical drives manufacturers and operators. In fact, both correct diagnosis and early detection of incipient faults lead to fast unscheduled maintenance and short downtime for the process under consideration. They also avoid harmful and sometimes devastating consequences of faults and failures. The topic is becoming far more attractive and critical as the population of electric machines has largely increased in recent years. The number of operating electrical machines has been around 16.1 billion in 2011, with a growth of about 50% in the last five years [1].

Electrical machines and drives are subject to many different types of faults. These faults include: a) stator faults which can be listed as stator open phase, stator unbalance due to short circuits or increased resistance connections; b) rotor electrical faults which include rotor open phase, rotor unbalance due to short circuits or increased resistance connections for wound rotor machines and broken bar(s) or cracked end-ring(s) for squirrel-cage induction machines, and rotor magnetic faults as demagnetization for permanent magnet synchronous machines; c) rotor mechanical faults such as bearings damage, eccentricity, bent shaft, and misalignment; and d) failure of one or more power electronics components of the drive system. Non-invasive monitoring is achieved by relying on easily measured electrical or mechanical quantities like for example voltage, current, external magnetic field, speed and vibrations. Other quantities, like internal flux or torque, are often estimated in drives control loops. Seldom, acoustic noise, temperature or other phenomena have been also investigated [2], [3].

A brief review of diagnostics techniques begins with the wide spread motor current signature analysis (MCSA), that is based on spectrum analysis of stator current signal, and is effective for machine operating at constant speed and rated load. Transient conditions are the most critical, and several methods have been proposed to deal with this situation. They are mainly based on discrete wavelet transform or Hilbert-Huang transform [4]-[7].

In order to give an insight into emerging new techniques related to condition monitoring and diagnosis of electrical machines, the following diagnosis topics have been selected:

- Diagnosis of stator winding insulation failures
- Diagnosis of rotor faults
- Diagnosis of rotor eccentricity
- Diagnosis of gear and bearing faults
- Fault diagnosis by stray flux analysis
- Fault diagnosis by Park's vector approach
- Diagnosis under non-stationary conditions
- Efficient digital signal processing techniques

2. Diagnosis of Stator Winding Insulation Failures

Initial studies proved that inter-turn short-circuits were one of the main root causes of insulation breakdown. As a consequence, a large number of researchers have focused their efforts in the on-line early detection and diagnosis of this type of failure [3]. Most of the proposed methods have demonstrated their reliability when experimentally applied to test benches based on low voltage motors, but they cannot be easily applied to large medium voltage (MV) motors with form-wound stator coils. In these machines, partial discharge analysis (PDA) is the most widely applied method. However, an important number of studies [8], that according to the variables used for diagnosis can be grouped into 13 categories [9], have also been developed for large MV motors.

Off-line analysis of stator insulation systems in rotating machines is performed by means of a set of tests that imply the machine disconnection from the power grid. The most relevant techniques are: a) measurement of insulation resistance and polarization index, b) AC and DC Hipot tests, c) turn-to-turn insulation tests, d) power factor (PF) tests, and e) PDA. Particularly, PF tests allow the user to obtain information, in an indirect way, about the partial discharge activity that is taking place in the bosom of the insulation system. One limitation of this method is related with the semiconductive protective layers located close to the output of the slots in the bars or individual coils that form the stator winding. These layers may hide the actual presence of partial discharges caused by insulation degradation, preventing a reliable diagnosis of the insulation system [10]. The problem can be minimized by using guard terminals if individual bars or coils are being tested (Fig. 1), however, when the test is carried out on a complete machine this solution is not feasible. According to the European Standard [11], this test allows the user to analyze the dielectric behavior of the insulation systems of rotating electrical machinery whose rated voltage is between 5 and 24 kV. In [12], it is developed a study demonstrating the inactivity of partial discharges in machines rated at voltages below 4 kV unless the internal status of the insulation is really poor. If this is the case, partial discharge activity is a clear indicator of an imminent fault [12], [13]. Therefore, it can be concluded that for voltages below 6 kV it could be difficult to make a proper early diagnosis of the internal status of the insulation system.

Fig. 1. Power factor measurement using guard terminals according to Standard IEEE 286. a) In a bar. b) In an individual coil.

Standard IEEE 1434, as well as IEC 60034-27 [9], are the most specific guides for the development of off-line PDA. So, again, a certain degree of uncertainty exists in the application of this test to machines whose rated voltage is below 6 kV since in this range the detection of partial discharge activity is linked to an extremely high level of wear in the insulation system, making the fault imminent [14].

3. Diagnosis of rotor faults

Specifically all the electrical faults that occurs in the rotor of an induction machine give rise to a common effect: a dissymmetry of the rotor circuits, both in the case of wounded machines (dissymmetry of the windings impedances) and in the case of squirrel cage machines (broken bars or cracked end ring). Rotor faults can be caused by thermal stress, electromagnetic forces, electromagnetic noise and vibration, centrifugal forces, environmental stress (abrasion), mechanical stress owing to lose laminations, fatigue parts, bearing failures, or defects in connections. Rotor faults are investigated considering constant and variable speed operating conditions, assuming power converters based supply. Usually, stator current is used as a measurement sensitive to the rotor faults and a suitable method to obtain a diagnostic index and a threshold stating the edge between faulty and healthy condition. Conventional MCSA based on the frequency analysis (FA) of the stator current is currently the most common and well-established technique. In fact, MCSA is simple and effective under suitable operating conditions. However, this technique has significant limitations because of increased complexity of electric machines and drives. As an example, MCSA is the optimal choice for machines under steady-state conditions and rated load. Here the diagnosis of a 7.5 kW squirrel-cage induction machine operated at variable speed is reported. The broken bar, artificially created in the machine, is detected by a demodulation method that report fault signatures on a localized fixed frequency. Under these conditions MCSA fails, as detailed in Fig. 2.a. In fact, the sideband components related to the faults are spread across a wide frequency range and are not detectable. The use of a suitable demodulation shows that effective condition monitoring is possible by frequency translation of the fault signature at frequency f=0 as shown in Fig. 2.b. [5]. Condition monitoring for rotor faults in induction machines is a very attractive topic, with special reference to quantitative, non-invasive methods, operating also in transient conditions [15].

Fig.2. Spectrum of phase current of an induction machine during acceleration. a) Using conventional FFT in healthy (light gray solid line) and faulty (solid line) conditions. b) Using demodulated current in healthy (light gray solid line) and faulty (solid line) conditions.

4. Diagnosis of rotor eccentricity

The rotors of power electrical machines are usually heavily solicited [16]. Mechanical, thermal, and magnetic unbalances invariably lead to rotor eccentricities (REs). REs should be carefully monitored in large machines, in unmanned plants, and everywhere damages result in costly service disruption and repairs. REs produce unbalanced magnetic pull, vibrations, and shaft currents, leading to bearing wear and damage, frame and winding loosening, insulation fretting, and stator-rotor rubs. REs were invasively monitored in large generators by using capacitive, inductive, and fiber-optic sensors. Phase current monitoring is a viable alternative for condition-based maintenance, due to easy of measurement [2]. The rotor slot frequencies in the phase current of induction motors (IMs) [17] or the sidebands $f \pm fr$ around the supply frequency [18] have been exploited. Load influence and difficulty to distinguish a static RE (SRE) from a dynamic RE (DRE) are open problems. Consequently, indicators of mixed RE overall level were tried. Separate detection of SRE and DRE by using terminal voltage analysis at machine switch-off is reported in [17]. The external flux is used in [19], where a DRE-related slip-frequency signature is detected by an axial coil. Although some methods suitable for IMs could be adapted to other revolving-field machines with a cage, the zero-slip condition and the salient poles require specialized approaches for synchronous machine (SM) monitoring. Reference [20] studied SM phase current and voltage harmonics in case of SRE, showing increasing non-homopolar triplen harmonics for series-connected stator windings. $2f$ and f/p frequencies were detected in the field current of SMs with SRE and DRE, respectively [20]. The split phase current signature analysis (SPCSA) may be used in case of parallel-connected windings [21]. The SPCSA exploits the air gap flux density modulation due to REs and resulting in additional $2(p\pm1)$-pole flux density waves in $2p$-pole machines. These waves affect the phase currents only thanks to the rotor cage, whose reaction field makes rise $f\pm fr$ frequencies in the line current in case of mixed RE [18]. The $2(p\pm1)$-pole flux waves however cause current circulation in the stator, and an unbalance in the split-phase currents. The latter can be transformed in complex space vectors. Both SRE and DRE can be assessed based on the fast Fourier transform (FFT) of the $2(p\pm1)$-pole space-vectors (Fig. 3).

Fig. 3. Virtual instrument panel, showing the SPCSA applied to a 1950kVA six-pole stand-alone alternator [21].

5. Diagnosis of Gear and Bearing Faults

Detecting and identifying mechanical faults and separating them from each other are major challenges in electrical drive systems. Although vibrations and acoustic noise are commonly used for this purpose, it is desired to detect faults using minimal standard sensors as the ones existing for other purposes like current and voltage sensors. The questions that are addressed in ongoing work are:

- Is it possible to determine the presence of a fault from measurements only at the drive, instead of at the bearings and gears? In [22] on bearing faults, and in [23] on gear faults such comparisons are presented and they were rather pessimistic when it comes to the use of stator current.

- Is it possible to separate faults with similar manifestations? What techniques can be applied on line with limited data storage capability and processing in low cost applications?

Types of mechanical faults in bearings and gears connected to electrical drives can be: bearings fail as pits are created possibly through bearing currents and voltages; uniform wear due to use and environment; gear wear resulting in backlash, or individual damage due to an impact or a manufacturing fault.

Mechanical faults translate into rotating eccentricities and torque pulsations and can also translate into electric quantities. Current variations are dependent not only on the fault, but also on the supply. A fast current controlled inverter may well decrease the effects of the eccentricity and the signs of the bearing fault. Bearing or gear faults are characterized by three effects: Frequency with which an impulse repeats, which depends on the rotation frequency; generation of vibration from the impulse that can be established experimentally; and an increase in the total level of noise.

The closer the sensors are to the damaged bearing or gears, the lower the damping and clearer the relationship between the fault and the sensed variables. Hence, determining the presence of these faults from the acceleration on the housing is the most accurate method. But the most convenient method of detection is to use existing sensors, e.g. for current or voltage of the drive. When the signal is stationary, FFT will suffice to give enough features for further processing. Time-frequency analysis methods are preferred for feature extraction in non-stationary cases, such as continuous wavelet transform, as well as short time Fourier transform, Wigner-Ville distribution and Hilbert-Huang transform [24]. Alternatively, time-domain rather than time-frequency features are used to estimate thresholding, root mean square, crest factor, and distribution measures [25].

Prognosis is based on a sequence of measurements and on tracking the evolution of a fault (Fig. 4). For data-based models, prognosis requires a large number of samples, or a clear trend leading to reliable extrapolation. Physics-based models that connect features to fault states and predict the fault developments have been proposed. Among them are particle filters and hidden Markov methods [26].

Fig. 4. Flow chart of information acquisition and processing for prognosis.

A wide range of fault diagnosis algorithms, based on models and signal processing methods have been compared, but no clear general choices seem to emerge. Physical models can be useful, but their parameters not easily determined ahead of use. Adapting of the model parameters over time is a promising solution. The trends in the diagnosis of mechanical faults then point to [27]:

- Use of more than one sensor for prognosis. This leads to more accurate indicators, e.g. the power to the inverter, or the transfer function between torque and speed as modified by fault.
- A combination of data-driven and model-based techniques to follow the fault development, and estimate the confidence in the predictions.

6. Fault Diagnosis by Stray Flux Analysis

Techniques based on vibrations or current signature analysis are widely used for electrical machines diagnosis because these variables are directly tied to the electrical or the mechanical state of the machine. However, over the last decades, methods based on the analysis of external magnetic field have been developed [28]-[31]. Their main advantages are the noninvasive investigation and the simplicity of implementation. The drawback of these methods is related to the difficulty for modeling the magnetic field that strongly depends on the electromagnetic behavior of the stator yoke and of the motor housing, which have an important shielding effect. The determination of the external magnetic field requires the modeling of the internal sources and the ferromagnetic and conducting materials of the machine that have an influence on the external stray flux. The computation of such a problem can be made using finite elements approach, but a lot of simplifications are necessary and the modeling requires a large computational effort [32]. Another approach consists in adapting analytical solutions existing for simple geometries which lead to define attenuation coefficients that can be easily combined with an analytical model of the machine [33].

The external magnetic field can be studied by the mean of its axial and radial decomposition. In this approach, the axial field is in a plan which includes the machine axis. It is generated by currents in the stator end windings or rotor cage end ring. The radial field is located in a plane perpendicular to the machine axis, it is an image of the air-gap flux density which is attenuated by the stator magnetic circuit (package of laminations) and by the external machine frame. The both fields can be measured separately by a convenient location of the sensor. Fig. 5 shows the different positions of a stray flux sensor, derived from the presumed circulation of the field lines. It enables to measure respectively the axial (Pos. 2) or radial fields (Pos. 3). Indeed, in Pos. 3 the stray flux sensor is parallel with the longitudinal plan of the machine, and the linked flux of the sensor concerned by the axial field is null. In Pos. 1 the sensor measures the radial field and also a part of the axial field. The pure axial field measurement can be done in Pos. 2.

Fig.5. Stray flux sensor in different measurement positions.

A stator inter-turn short-circuit fault produces a dissymmetry in the airgap flux density and therefore in the external magnetic field. This dissymmetry generates flux density components that will clearly appear in the stray flux as it is not strongly attenuated by the stator iron.

It can be pointed out that the sensitivity of the external magnetic field is higher than the line current as far as these spectral lines are concerned. It should be also noted that the lower part of the spectrum with frequency less than the sensitive slotting effect are not very sensitive to the fault [34].

It is well known that a broken bar in induction machines generates a negative sequence on the rotor fundamental airgap flux density. The direct and indirect consequence is the appearance of the spectral lines in the line current spectrum that also appear in the stray flux. It can be shown that eccentricity has also an influence on the phenomenon. It should be point out that this phenomenon is specific to the axial field and does not appear in the radial field, neither in the line current [34].

7. Fault Diagnosis by Park's Vector Approach

This section reviews recent advances in fault diagnosis by Park’s vector approach, with special emphasis being given to the most recent developments concerning power converter fault diagnosis in variable speed ac drives. With the aim to demonstrate the suitability of such approach for power converters self-diagnostic, an experimental-based assessment of four algorithms intended for real-time diagnosis of switch open-circuit faults is presented.

The Park’s vector approach has been used successfully for conditioning monitoring of electromechatronic systems – including three-phase power transformers, synchronous and asynchronous machines, and power converters – permitting to diagnose several types of malfunctions [35]-[39]. As main merits, this approach is non-invasive and requires non-expensive sensors and measurement systems. The first studies were based on the recognition of the pattern associated with the current Park’s vector representation. For instance, the extended Park’s vector approach relies on the spectral analysis of the AC level of the current Park’s vector modulus, whereas through the average current Park’s vector approach converter power switch faults are detected when the vector modulus is different from zero. However, load dependency and sensitivity to transients were major drawbacks in converter diagnosis, which were finally overcome by the use of the Park’s vector approach in recently proposed techniques [38]-[39].

Concerning power converter self-diagnosis based on the Park's vector approach, the modulus of the Park's vector is used in [38] to normalize the phase currents, and the absolute value of the absolute Park's vector phase derivative is used in [39] as a detection variable. With further signal processing and additional variables, both techniques are able to diagnose multiple faults, being the technique reported in [38] called the errors of the normalized currents average absolute values (ENCAAV), and the technique reported in [39] the current Park’s vector phase and currents polarity (CPVPCP). Both techniques fulfill the major requirements for integration into the drive controller for real-time diagnosis, such as the lack of need for extra hardware, simple implementation, operating condition independence and low computational demand. With identical features, two other distinct techniques have been proposed, the normalized currents average values (NCAV) [40], and the normalized reference current errors (NRCE) [41].

A comparison of the four aforementioned techniques [38]-[41] constitutes a valuable contribution for assessing their applicability to a specific drive system. The four methods were integrated into a digital controller of a permanent magnet synchronous motor (PMSM) drive and the experimental results obtained were used to evaluate their performance. In summary, the most relevant information of the performance comparison is shown in Table I. More detailed information can be found in [37]. All methods demonstrate very high diagnostic effectiveness, even for low load levels. The CPVPCP method is endowed with a remarkable robustness against false alarms as a consequence of load and speed transients. The fastest detection can be achieved by using the NRCE method. NRCE and ENCAAV methods are the less computational demanding ones. Finally, the ENCAAV method involves the lowest tuning effort.

TABLE I
FAULT DIAGNOSTIC METHODS KEY FEATURES EVALUATION

8. Diagnosis Under Non-stationary Conditions

A machine works under non-stationary conditions when its normal duty cycle consists of continuous and random load fluctuations and/or changes in supply conditions (Fig. 6.a). Wind generation, electrical vehicles, or in general, industrial processes that involve variable speed drives are examples of actual applications in which machines work under non-stationary conditions. Traditional approaches based on stationary analysis – as MCSA - usually lead to unsatisfactory results when are applied under such as conditions. On the other hand, more recent approaches based on transient analysis, usually focused to the startup cannot be applied to diagnose under non stationary conditions. Therefore new diagnostic methodologies have to be developed. A summary of recent proposed methods for performing diagnostic in non-stationary conditions is given next:

- Frequency domain approaches: When speed oscillations are small, Fourier analysis can be applied providing that not great accuracy in diagnostic is needed. The unavoidable smearing effect in the spectrum could be limited shortening the time of capturing the signal, in order to reduce the slip changes. But this leads to bad quality spectra with low frequency resolution and high spectral leakage. To solve this conflict, methodologies based on the estimation of signal parameters via the rotational invariance technique (ESPRIT) have been proposed [42].

- Time domain analysis: Under non-stationary conditions, different failures introduce fault components into the analyzed signals, with amplitude and frequency changing with time in an unpredictable way, since speed varies randomly. Consequently, there are not specific fault related patterns in time domain which support the diagnostic. Nevertheless, the appearance of components related to the fault, which frequency changes in a limited interval, produces increases of energy of the signal, in this range of frequency (Fig. 6.b). Works presented in [43]-[45] propose to diagnose and quantify the faults through the calculation of the signal energy in specific frequency bands. Discrete wavelet transform (DWT) is used in these works as a filtering tool for extracting the frequency bands of interest and then computing the signal energy into them.

- Diagnosis in slip-frequency domain: This kind of analysis is complementary to the time domain approaches, since it enable for characterizing the faults components under non stationary conditions, with high reliability. This analysis is based on the description of the instantaneous frequency of an extracted fault component against slip. It is easy to demonstrate [45] that this plot is a straight line, with specific slope and offset for every kind of fault. This fact enables for identifying faults and discriminating then of other phenomena as load and voltage fluctuations or noises that can increase the signal energy. The analysis in slip-frequency domain has been successfully applied to diagnosis of rotor and stator asymmetries [45] as well as eccentricity in induction machines [46]. An example of this kind of analysis is shown in Fig. 6.c.

- Diagnosis in time-frequency domain: This kind of analysis can be performed through different continuous transforms as short time Fourier transform, continuous wavelet transform (linear transforms), or Wigner-Ville distribution, Choi-Williams distribution and Zhao-Atlas-Marks distribution (quadratic transforms). The standard result of these transform is a 3-D graph usually plotted as a 2-D colored map. For each time, this map informs about how the signal energy is distributed among different frequencies. This enables to track the evolution of the fault components during transients and non-stationary operating conditions. A recent improvement in the field of linear transforms is proposed in [47], where an adaptive transform is introduced taking into account the characteristics of the presumed fault component in each point (Fig. 6.d). Regarding quadratic transforms, in [48] a method based on a pre-treatment of the diagnostic signal through optimized notch filters is proposed for reducing the cross terms but avoiding the use of kernels, keeping unaltered the characteristic high resolution of the Wigner-Ville distribution.

Fig.6. Diagnostic under non-stationary conditions. a) Fluctuating speed and current. b) Increase of energy in the frequency bandwidth [0Hz, 39Hz] in case of stator phase asymmetries. c) Diagnostic in the slip-frequency domain of a cage machine with mixed eccentricity. d) Diagnostic of a bar breakage in time-frequency domain trough an adaptive transform.

9. Fault diagnosis and efficient Digital Signal Processing techniques

The early detection of incipient faults with minimum required measurements is the main purpose of an ideal diagnosis. Non-invasive techniques are good candidates in this sense because they do not need any change in the system design. A general scheme of non-invasive electrical machine fault diagnosis is shown in Fig. 7. It consists in an initial stage for signal conditioning in order to enhance the signal-to-noise ratio (SNR) and to avoid aliasing. In a second stage, the data sampling converts the analog signal into a discrete one. These two parts are integrated in one module in modern data acquisition systems. Sampled three-phase voltages and currents can be used directly or for estimation of other quantities such as mechanical speed and mechanical torque based on estimators or observers. In order to cover a large number of faults, different features should be extracted from a signal or its estimation in order to allow accurate fault classifications. A reliable decision-making procedure is important at the final stage which avoids missing or false alarms.

Fig. 7. General implementation scheme for non-invasive electrical machines fault diagnosis.

Classical digital signal processing techniques (DSPTs) such as discrete Fourier transform (DFT), which is known as an efficient algorithm in terms of computation time, have been used for feature extraction for a long time [49]. Any kind of faults in electrical machines may yield to asymmetries in its electromagnetic field, adding characteristic fault frequencies to any initial sensor signal and depending on the type of fault. This can be well explored by means of the frequency domain analysis. Despite their effectiveness, classical DSPTs have several limitations to be evaluated for a reliable fault diagnosis. The main restriction is the practical usage of classical techniques on real signals because of additional noises which are always present in any industrial environments. This may result in erroneous decision-making process. The study of advanced DSPTs plays a crucial role as it can be used to enhance SNR and consequently to improve extraction performances. By handling time-varying conditions, this leads to more consistent fault detection techniques. Furthermore, thanks to recent advances in digital signal processing technology, adequate DSPTs can be implemented on cost-effective real-time platforms. The advanced DSPTs which have been recently proposed for improving performances of fault diagnosis in induction machines can be classified into three different categories [50]: a) Frequency domain analysis; b) Time-frequency/time-scale domain analysis; c) Time domain analysis.

In the frequency domain, the frequency resolution is a crucial factor since any accurate frequency tracking in a spectrum is essential for a consistent diagnosis since the fault related frequency components in electrical signatures are commonly load-dependent. The modern DSPTs which are used for improving frequency resolution of spectrum are classified in nonparametric, parametric and subspace techniques. It is shown that the application of subspace methods can improve significantly the performance of fault diagnosis in induction machines in the frequency domain in comparison with non-parametric and parametric methods due to their ability to estimate frequencies with high resolution using smaller samples measurement and reducing the noise influence [50].

Electrical machines working in non-stationary operating conditions have non-stationary voltage, current, vibration and so on. A straightforward solution for processing of a non-stationary signal is to represent it in the time-frequency plane. A well-known method, which has been widely used due to its robustness and its simplicity for electrical and mechanical faults detections in induction machines, is the windowed Fourier transform (WFT). Quadratic time-frequency analysis techniques are efficient alternatives to the WFT due to their independence from the type or the size for the window function. The Wigner-Ville distribution (WVD) and its variants, particularly the pseudo-WVD (PWVD) and the smoothed pseudo-WVD (SPWVD) have been used for mechanical faults detections in electrical machines. The WVD produces large undesirable frequencies, the so-called inner interference terms, which can interfere with fault-related frequency components by decreasing the ability to evaluate the fault severity. The PWVD and SPWVD methods attempt to reduce the magnitude of inner interference terms by smoothing in both time and frequency planes. To achieve a strong reduction of inner interference terms in addition with high frequency resolution, the Choi-Williams distribution (CWD) and the Zhao-Atlas-Marks technique (ZAM) have been applied. Another concept which is extensively used for electrical machine diagnosis is the wavelet transform (WT). The fundamental idea is to replace the frequency shifting operation which occurs in the WFT by a time scaling operation. This makes the WT a time-scale representation rather than a time-frequency one. This method has been applied to the stator current of induction machines during the plugging and removing the grid connection modes of operation in order to extract a general pattern for fault characteristic frequencies [50].

10. Conclusion

The condition monitoring of electrical machines has been initially dedicated to purely internal electrical and mechanical fault detection and today, it covers monitoring in voltage source inverters, load and some other elements of the mechanical transmission system too. The first techniques have been implemented to be applied on stationary conditions of electrical machine drives by using the FFT in order to localize the frequency components associated to different faults. At present, this conventional technique is still used as a first diagnostic approach but real conditions of industrial applications make that it cannot be the only support for the development of diagnostics tools. New techniques based on the assessment of physical phenomena produced by fault conditions, advanced digital signal processing and reliable decision-making procedures, show the state-of-the-art of recent methodologies for efficient condition monitoring of electrical machines. However, the reliable identification and isolation of faults is still under investigation and there are several open issues. Among them, the insensitivity to operating conditions, the fault detection for drives in time-varying conditions, the evaluation of fault severity and the fault-tolerant control for drives have been recently under focus.

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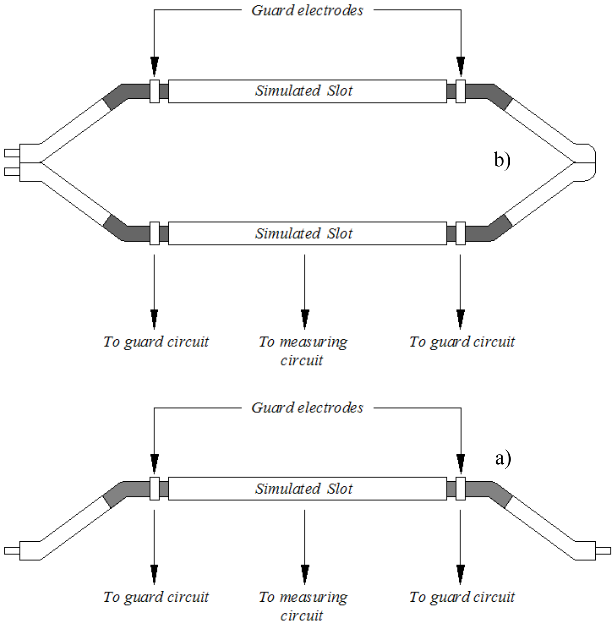
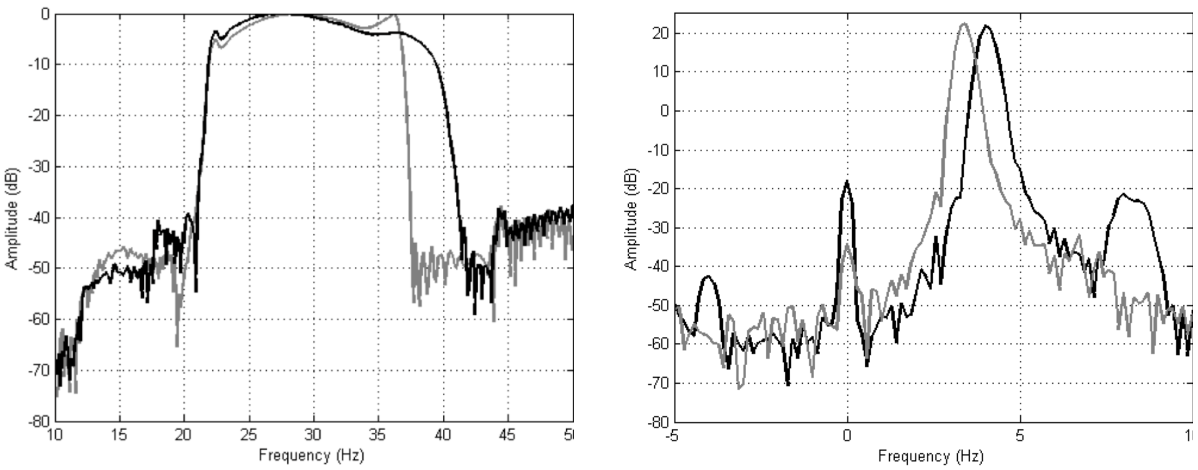
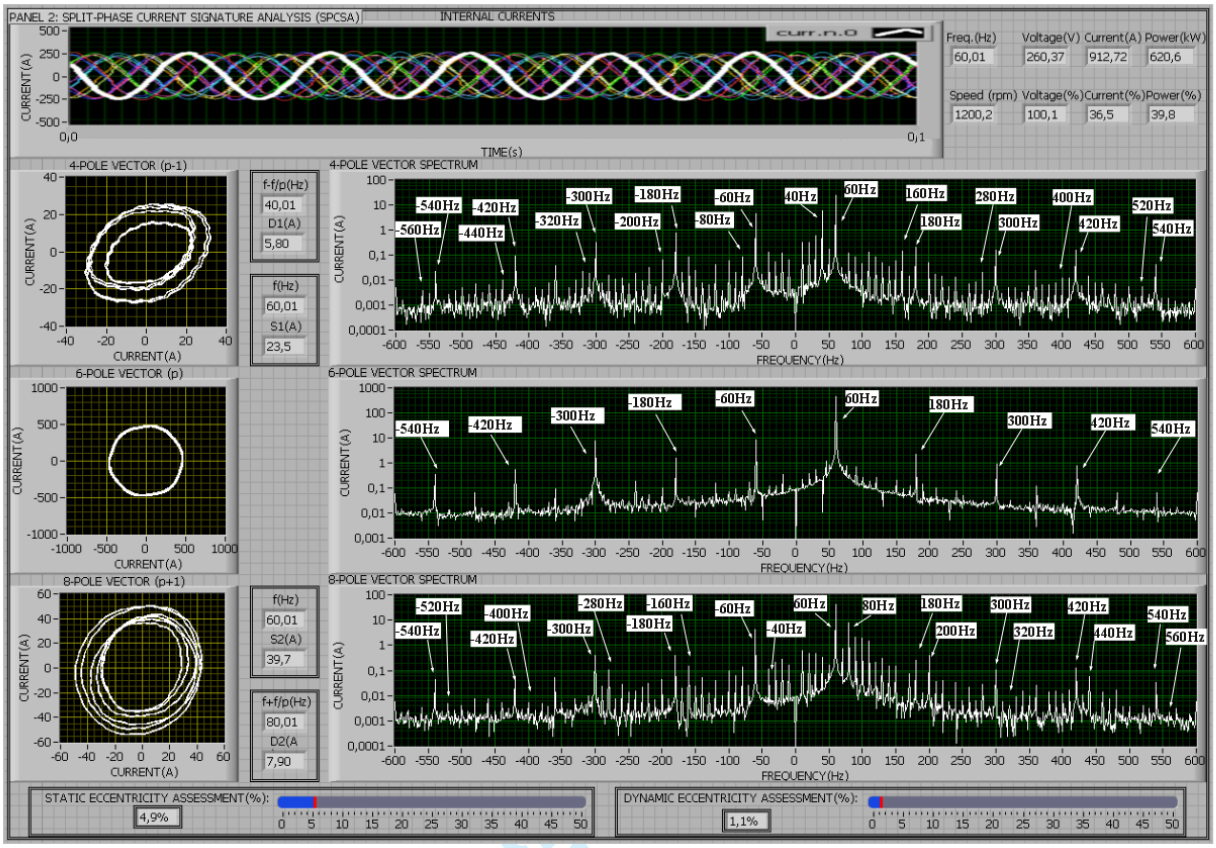


Fig. 1. Power factor measurement using guard terminals according to Standard IEEE 286. a) In a bar. b) In an individual coil.



a) b)

Fig.2. Spectrum of phase current of an induction machine during acceleration. a) Using conventional FFT in healthy (light gray solid line) and faulty (solid line) conditions. b) Using demodulated current in healthy (light gray solid line) and faulty (solid line) conditions.



Freq.(Hz) 60,01
Voltage(V) 260,37
Current(A) 912,72
Power(kW) 620,6
Speed (rpm) 1200,2
Voltage(%) 100,1
Current(%) 36,5
Power(%) 39,8

f-f/p(Hz) 40,01
D1(A) 5,80
f(Hz) 60,01
S1(A) 23,5
f(Hz) 60,01
S2(A) 39,7
f+f/p(Hz) 80,01
D2(A 7,90

STATIC ECCENTRICITY ASSESSMENT(%): 4,9%
DYNAMIC ECCENTRICITY ASSESSMENT(%): 1,1%

Fig.3. Virtual instrument panel, showing the SPCSA applied to a 1950kVA six-pole stand-alone alternator [21].

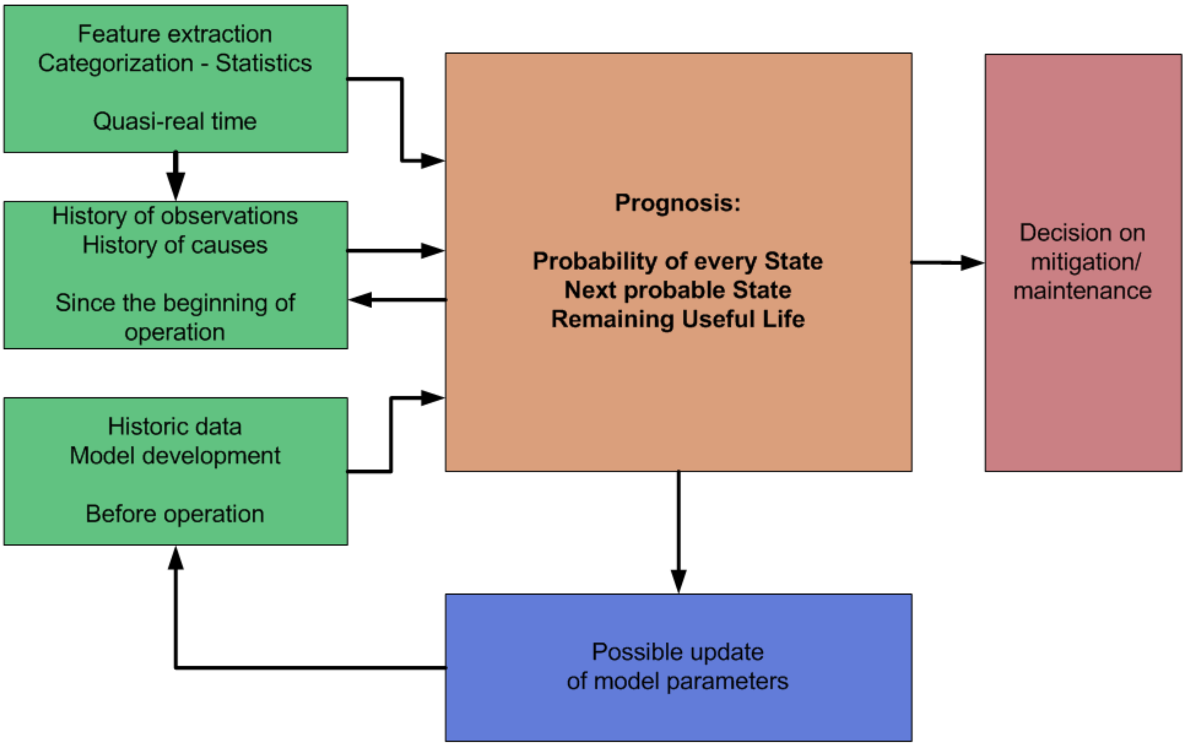


Fig.4. Flow chart of information acquisition and processing for prognosis.

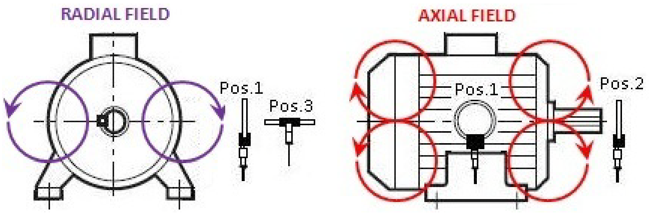
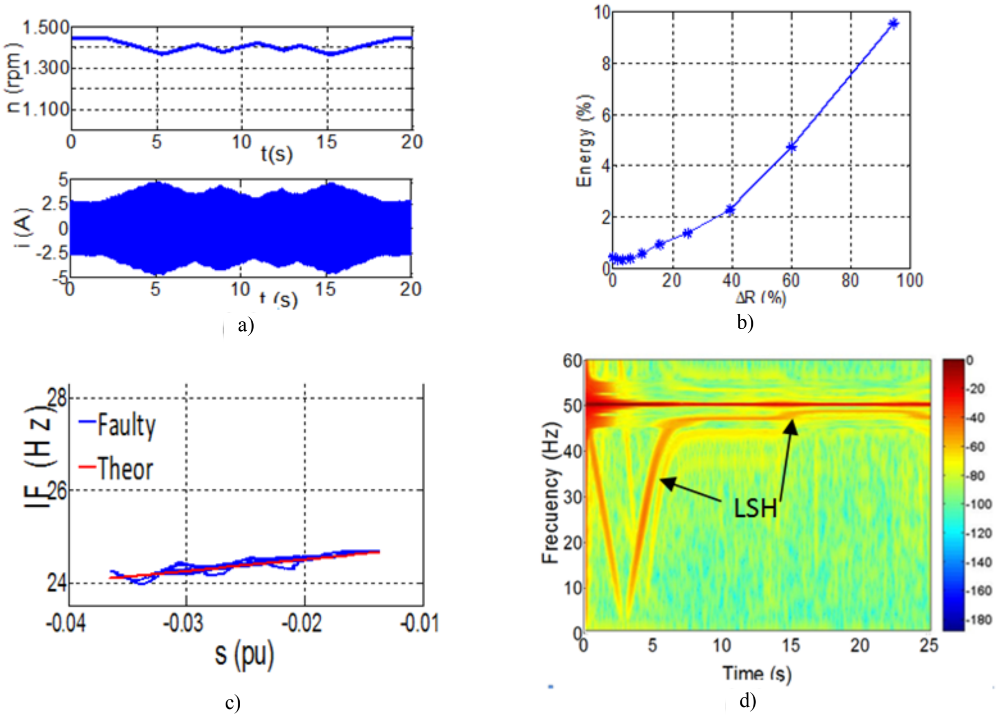


Fig.5. Stray flux sensor in different measurement positions.

TABLE I
FAULT DIAGNOSTIC METHODS KEY FEATURES EVALUATION

		ENCAAV [38]	**CPVPCP [39]**	**NCAV [40]**	**NRCE [41]**
Localization Capabilities (Fault Signatures)		15	27	27	27
Effectiveness		High	High	High	High
Robustness (Robustness Factor)		0.76	1.00	0.23	0.94
Detection Speed (% Currents Period)	Min	11.3	37.8	25.9	4.8
	Max	77.3	92.4	88.6	66.5
	Avg	39.6	71.2	58.3	28.7
Implementation Effort (File Size in kB)		64.9	73.1	74.7	63.4
Computational Burden (Execution Time in µs)		3.40	4.25	4.89	3.37
Tuning Effort (Parameters Number)		2	4	3	3



a)

b)

c)

d)

Fig.6. Diagnostic under non-stationary conditions. a) Fluctuating speed and current. b) Increase of energy in the frequency bandwidth [0Hz, 39Hz] in case of stator phase asymmetries. c) Diagnostic in the slip-frequency domain of a cage machine with mixed eccentricity. d) Diagnostic of a bar breakage in time-frequency domain trough an adaptive transform.

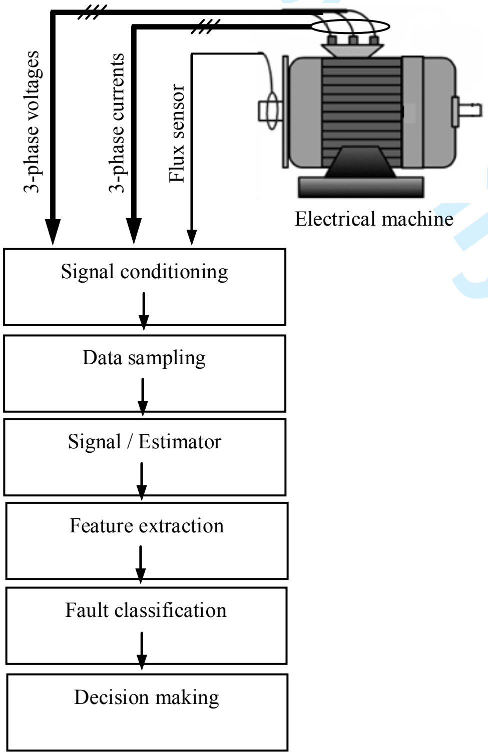


Fig.7. General implementation scheme for non-invasive electrical machines fault diagnosis.