Electrical machines fault detection

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What is diagnostics?

Diagnostics is a procedure of “translation” of the information arising from the measurement of parameters related to a machine (or a system) in information regarding the effective or incipient faults of the machine itself.

In other words, diagnostics is the complex of the activities of analysis and synthesis which - by using the acquisition of certain physical quantities, characteristic of the monitored machine - allows to draw significant information on the condition of the machine and on its trend during the time, for the evaluation of its reliability in short and long term.

What is diagnostics?

The targets of the diagnostics are:
- detection if the fault is present (or not)
- isolation in which part of the machine
- identification which kind of fault

The general problem of diagnostics is to detect if a specific fault is present (or not) on the basis of the available information, preferably without an intrusive inspection of the machine.
Hypothesis test

This problem can be described with a statistical approach as a problem of hypothesis test:
- null hypothesis $H_0$: the fault is present;
- alternative hypothesis $H_1$: the fault is not present.

The hypothesis test is subject to two types of error:
- **type I error** happens when the null hypothesis $H_0$ is true and you reject it: when, on the basis of the available information, you decide that the fault is not present, but actually it is. Therefore, the machine is not stopped and repaired before the effective manifestation of the failure, with possible catastrophic consequences.
- **type II error** happens when the null hypothesis is false and you fail to reject it: when, on the basis of the available information, you decide that the fault is present, but actually it is not. Therefore, the machine is stopped and repaired in vain, with useless economic costs.

Steps of diagnostics

Diagnostics is not an exact science!

A diagnostic program develops according to the following steps:
- a) data acquisition,
- b) data processing,
- c) decision-making.

The methods employed for the acquisition and elaboration of the data and for the choice of the threshold which separates the faulty condition from the healthy condition of a component can heavily influence the chance to make an error during the phase of the decision making.

If the decision is made by an individual, we can talk about “fault detection”, if the decision is given by an automatic algorithm, we can talk about “diagnosis”.

Subject of diagnostics

If the subject of diagnostics is a rotating electrical machine, it is important to note that its operation cannot be considered separately from:
- the operation of the mechanical machine connected along its axis line (pump, fan or another load for an electrical motor; turbine or another prime motor for an electrical generator);
- the type of the mechanical coupling (joint, gears, belts, etc.);
- the possible control system (inverter, etc.).

All these mechanical and electronic systems can:
- induce faults in the electrical machine,
- arouse changes in the parameters of the electrical machine, even in absence of fault;
- experience faults induced by the electrical machine.

Main parts of cage induction motor

In this seminar we consider, as subject of diagnostics, the three-phase induction motor and, in particular, the type with cage rotor, since it is more widespread with respect to the wound rotor.
Main parts of cage induction motor

For higher power and voltage, the manufacture characteristics are different: different insulation of the stator windings (form-wound) and rotor bars inserted in the slots and welded to the short-circuit rings (not die-cast).

Wound stator and cage fabricated rotor of a three-phase induction motor of 1.8 MW, at 6 kV

Where the faults can happen in the motors?

In the literature, only two extensive (and quite old) surveys on the faults in electrical motors are present, one dated 1985 and the other one 1995: since the latter is limited to the petrochemical industry, normally we refer to the results reported in the first survey, developed by the Electric Power Research Institute (EPRI):

Diagnostics and condition monitoring require the measurement and the analysis of some signals that contain characteristic information (symptoms) about the process of wear, malfunctions or incipient faults. The following factors should be considered in the selection of the more appropriate diagnostic techniques:

1) The sensor should be (possibly) non-invasive;
2) The sensor and the measurement system must be reliable;
3) The diagnosis must be reliable;
4) The severity of the problem should be quantified;
5) Ideally, you should have an evaluation of the remaining life time;
6) Ideally, the information obtained from the sensor should provide an indication of the “root causes” which produced the fault.

Note that the frequency of occurrence of these faults depends heavily on the specific application of the machine.

Possible indicators of fault

In many cases, it is possible to meet the criteria from 1) to 4), whereas those from 5) to 6) are extremely difficult to achieve.
**Possible indicators of fault**

In an electrical machine, different aspects (electrical, magnetic, mechanical, fluid dynamics, thermal) interact in a complex manner, as shown in the figure:

Various parameters belonging to these different fields can be suitable as potential fault indicators in electrical machines:

- **Electromagnetic:**
  - current, voltage
  - partial discharges
  - magnetic fluxes (internal and external)
- **Mechanical:**
  - vibrations (displacement, speed, acceleration)
  - noise (acoustic emission)
- **Other (thermal, chemical):**
  - temperature
  - analysis of oil and gas (only for transformers)

Further possible indicators of fault are:

- the measurement of the **efficiency**, which requires the measurement of both input and output power, therefore both electrical and mechanical parameters in case of rotating electrical machine.
- the **visual analysis** of different parts of the machine, during the revisions involving their dismantling: this analysis is based on objective parameters, but also on the experience of the technical staff.

If present, the **control and supervision** system, governing the overall installation, and the **power electronics**, specializing in translating the commands in energy signals supplied to the machine, can be considered as important parts in the scheme of diagnostics and condition monitoring.

**MCSA to detect induction motor faults**

In the last years, the traditional diagnostic techniques, based on the vibration measurement, have been progressively abandoned in favour of an approach focused on the **analysis of electromagnetic signals**, in particular the **stator current** (MCSA) and the external **stray flux** around the motor.

The aim is to employ **less sensors**, possibly already present in the electrical drive for the control of the machine.
MCSA to detect induction motor faults

The possible faults which can be detected by means of MCSA are:

1) Broken rotor bars
   - slowly progressive faults
   - primary effect on airgap flux and therefore on stator current
   - well known and established methodology, from many years

2) Rotor eccentricities
   - quickly progressive fault

3) Stator short circuits
   - primary effect on airgap flux and therefore on stator current
   - well known theory, but still not applied in real cases

4) Bearing faults
   - secondary (and often weak) effect on airgap flux and therefore on stator current
   - well known theory (but not valid for any type of bearing fault), still not applied in real cases

Broken rotor bars can be a serious problem, especially for large induction motors with heavy duty cycles. Broken rotor bars do not directly cause a breakdown of the motor, but they can give rise to severe secondary effects: the fault mechanism can result in broken parts of the bar hitting the stator winding. This can cause a serious mechanical damage to the insulation of the stator winding, with a consequential winding failure, resulting in a costly repair and lost production.

Broken rotor bars or end rings can be caused by:
- Direct-on-line starting duty cycles for which the rotor cage winding was not designed to withstand;
- Pulsating mechanical loads;
- Imperfections in the manufacturing process of the rotor cage.


In general, induction machines can be equipped with the following types of rotor:
- **wound rotor**, with three-phase winding consisting of copper wires and three short-circuit rings.
- **squirrel cage rotor**, with a multi-phase winding consisting of bars and two frontal short-circuit rings at opposite sides. The cage rotor can be die-cast or fabricated (with the bars inserted in the slots and welded to the frontal rings). In the first case, the bars are almost always made of aluminium (but they can be made of copper or copper alloys), whereas in the second case they are almost always made of copper.
**Die-cast cage rotor**

The die-cast cage rotor is normally used in low and medium power induction motors (about <250 kW). The whole cage is formed in a single piece by pouring molten metal (usually aluminium) into a mould. The bars are generally skewed with respect to the stator slots.

In recent years, the manufacturing technique of die-cast copper cage rotors is spreading (until tens of kW), in order to improve the motor efficiency. The manufacturing process of this type of rotor, compared to the die-cast aluminium cage, presents higher energetic and economic costs and it is technically more complex.

(copper melts at 1083 °C, aluminium at 658 °C)

**Fabricated cage rotor**

For high power induction motors (about >250 kW), which can be supplied at low (<700 V) or high voltage (>700 V), the rotor consists of copper bars that are inserted into the slots and welded to the frontal short circuit rings.

Other examples of fabricated cage rotors:

- 2800 kW, 6600 V, 2 poles
- 900 kW, 6000 V, 8 poles
- Fabricated cage rotor for a 3 MW motor, 6 kV, 2 poles
- 300 kW, 3300 V
Broken bars in fabricated cage rotor

For these rotors, the most likely failure is due to the breakage of a bar or a fracture near the point of contact between bar and ring.

- 900 kW, 6 kV, 8 poles
- 3100 kW, 11 kV, 2 poles

Phenomenon of rotor bar breaking

This failure is generally caused by thermal stresses and frequent start-ups.

This deterioration is slowly progressive, therefore a diagnostic tool can be effective in preventing it!

The start-up is a critical phase for the cage: the high temperature produced by the high currents (until 8-10 times the rated one) causes expansion of the bars, favouring the possible occurrence of fractures or detachments at the point of contact between bar and ring (due to mechanical fatigue, welding failure, etc.).

The consequent increase of impedance in the bar subject to the failure results in a redistribution of the currents in the healthy bars, arousing an imbalance of the magnetic flux produced by the rotor, which in turn causes an imbalance in the stator currents.

Effects of rotor bar breaking

The imbalance of the stator currents produces a backward rotating field.

As a consequence, there will be an increase of the currents in both windings (remarkable on the rotor, lower on the stator) and an increase of their temperatures.

The redistribution of the currents in the healthy bars, associated with the temperature increase, results in increased mechanical and thermal stresses on the adjacent bars to the broken one.

This causes the propagation of the failure.

This is usually a chain phenomenon, as the first broken bar causes more stress on the adjacent bars, which therefore deteriorates more quickly.
Symmetric rotor

- Speed of stator rotating magnetic field: \( f_1 = \frac{f}{p_p} \)
- Speed of rotor rotating magnetic field with respect to the rotor itself: \( f_2 = sf_1 = \frac{sf}{p_p} \)
- Rotor mechanical speed: \( f_r = (1-s)f_1 = (1-s)\frac{f}{p_p} \)

Asymmetric rotor

- Speed of stator rotating magnetic field: \( f \)
- Frequency of the stator current: \( sf \)

The stator "sees" the rotor rotating magnetic field at speed: \( sf_1 + f_r = sf_1 + (1-s)f_1 = f_1 \)

Motor current signature analysis

So, the left current component, at frequency \( (1-2s)f \), is directly related to the rotor failure, while the right current component, at frequency \( (1+2s)f \), is caused by the speed ripple effect and its amplitude varies with the value of the combined rotor-load inertia. The effect of the speed ripple also affects the amplitude of the left current component.

In general, the detection of broken bars based on the current sidebands analysis at frequencies \( (1\pm2s)f \) is successful.

In the following, the experimental results related to a motor with aluminium die-cast rotor, 1.5 kW, 220 V, 50 Hz, 4 poles, nominal slip 6%, 28 rotor bars are presented. Three rotors were tested: i) healthy, ii) with one broken bar, iii) with two broken bars.
Motor current signature analysis

The amplitude of the sidebands at frequencies \((1\pm 2s)f\) in the stator current spectrum depends on:
- number of broken bars (increases with the number);
- load percentage (increases with the load).

External stray flux

In the same experimental tests, the e.m.f. induced by the external stray flux has been measured by means of a sensor consisting of 300 turns wound on a C-shaped magnetic core of rectangular cross-section (25x10 mm²), positioned on the motor frame.

The external stray flux is the magnetic flux that radiates outside of the motor frame. Its magnitude is related to the place where the sensor is located around the machine body.

It is induced by both the stator and rotor currents, even if stator currents prevail, due to the magnetic shield effect provided by the stator against the rotor currents. Specifically, one or two stator phase currents dominate, due to the fixed position of the sensor and the distribution of the three-phase stator winding.

External stray flux

It is expected that stray flux includes the same information obtained by the stator current.

In fact, the sideband components at frequencies \((1\pm 2s)f\) are still present. As before, their amplitudes depend on the machine load.

Notice that the right side component amplitude increases with slip more than the left one, because the e.m.f. (i.e. the flux derivative) is measured instead of the flux. The signal is weaker than the stator current.

In summary, stator current and stray flux signals can be used with the same effectiveness in order to detect and quantify rotor faults.

The optimal choice depends on the specific application and on the easiness of installing flux or current sensors in the specific industrial environment.
Issues in the detection of broken bars

In practice, motors with a limited number of broken bars are usually still able to perform their operation without evident anomalies, as increased mechanical vibration or lengthening of the run-up time.

However, the motor does not remain in this condition for a long time, since the aging process is greatly accelerated by the chain reaction above described.

One issue in the detection of broken bars by MCSA is that the amplitude of the spectral components of the stator current due to a single broken bar is often in the order of magnitude of that induced by the intrinsic constructive asymmetries of a healthy machine, and therefore it is difficult to distinguish between the two cases.

Issue due to oscillating torques

Moreover, an oscillating torque produced by the load, without the presence of rotor asymmetries or rotor failures, produces sidebands in the stator current spectrum which, in some cases, may appear close to the frequencies due to the broken rotor bars.

Therefore, for a more in-depth (but also more expensive) diagnostic analysis, it may be useful to consider together different electromagnetic and mechanical parameters, measured by current probes, flux sensors, accelerometers and temperature transducers.

Radial vibration spectrum

Here we can see that even the amplitude of the sidebands at frequencies $f_r \pm 2sf$ in the spectrum of the radial vibration depends on:

- number of broken bars (increases with the number);
- load percentage (increases with the load).

a) at no-load
b) at half load
c) at full load

Red: healthy  Blue: faulty

1 broken bar  2 broken bars

Issue due to the rotor bar skewing

Practically, almost cage rotors are skewed:

Pros:
- Reduction of torque ripple (reduction of the parasitic torques and the consequent risk of cogging during the startup)
- Noise reduction during the normal operation

Cons:
- Increase of the inter-bar currents
Rotor bar skewing and its effects

The inter-bar current is the current flowing between adjacent bars of a cage rotor, through the magnetic iron core, which produces a non-uniform distribution of the current along the axial length of the machine.

Since there is no insulation between bar and core, only the bar-core contact resistance limits the current flowing in the core.

Some researches have highlighted that this contact resistance is about 70 times greater than the iron resistance.

In the classical theory of induction machines, the inter-bar currents are generally neglected.

The usual assumption is that aluminium (or copper) bar resistance is much lower than iron core resistance and bar-core contact resistance, so the current completely flows along the bars.

Other researches have shown that:

- Inter-bar currents become remarkable when a bar is broken;
- Resistivity between bars is lower in case of copper die-cast rotors than aluminum die-cast rotors.

If inter-bar currents are relatively high even in a healthy motor, then, in case of broken bar, the current flowing between the adjacent bars to the broken one (near to the short circuit ring, where the break is present) will become higher, causing a chain reaction that could more easily break the adjacent bars.

From a diagnostic point of view, these high inter-bar currents can reduce the imbalance caused by a broken bar: this effect can make harder the early detection of the broken bar, when the sidebands currents around the fundamental are monitored.

Effect of the inter-bar currents on the diagnostics

The diagnostic procedure based only on the stator current analysis for the detection of a broken rotor bar may fail if remarkable inter-bar currents are present, since they reduce the degree of asymmetry of the rotor and, consequently, the amplitude of the considered spectral components.

On the other hand, the presence of inter-bar currents has a further effect on the rotor vibrations: the interaction of the radial magnetic flux with the inter-bar currents, which flow tangentially along the rotor circumference, produces a force (and hence a vibration) in the axial direction.

Therefore, the analysis of the previously considered parameters (stator current, stray flux, radial vibrations) together with the axial vibration can increase the effectiveness of the proposed diagnostic procedure.
Effect of the inter-bar currents on the diagnostics


The graphs in the previous slide refer to a small induction motor (1.5 kW, 4 poles) with die-cast aluminium cage: in this case, the currents between bars in presence of one or two broken bars are negligible and the rotor diagnosis by means of the stator current analysis is still effective.

Another research has considered a higher power motor (55 kW, 2 poles, with copper cage and skewed bars) and has verified that a broken bar modifies the axial vibrations at particular frequencies.


Airgap eccentricity

Airgap eccentricity causes a force on the rotor, called Unbalanced Magnetic Pull (UMP), that tries to pull the rotor even further from the stator bore centre, in the direction of the minimum airgap. If the levels of eccentricity are not kept within specified limits (typically <10%), then eccentricity can cause excessive stress on the motor and can increase bearing wear.

Moreover, the radial magnetic force waves produced by eccentricity act on the stator and rotor, thus exposing the stator and rotor windings to potentially harmful vibrations. Besides, acoustic noise levels can substantially increase.

High UMP due to severe airgap eccentricity can ultimately lead to a rotor to stator rub, with consequential damage to the stator core, stator windings and rotor cage. This can cause insulation failure of the stator winding or breaking of the rotor cage bar or end rings and, hence, a costly repair, in case of high power induction motor.
**Airgap eccentricity**

Airgap eccentricity can occur due to manufacturing tolerances, installation procedures (in large motors), other damages or wear and tear. When the rotor can be considered as rigid and the motor is equipped with rolling bearings, as in the most induction motors, the airgap eccentricity can be distinguished in two types, **static** and **dynamic**, which can exist simultaneously (mixed eccentricity).

**Static eccentricity**

- The rotor rotates around its axis, which coincides with the shaft axis, but does not coincide with the stator axis.
- The rotor is symmetrical to its axis, so there is no mechanical imbalance.
- Static eccentricity can be caused by a misalignment due to constructive tolerances, bearings wear, stator core ovality or incorrect positioning of the rotor or stator.

**Dynamic eccentricity**

- The rotor rotates around the stator axis but not around its axis.
- The shaft axis does not coincide with the rotor shaft.
- Therefore, dynamic eccentricity arouses also a mechanical imbalance, i.e. a centrifugal force rotating at the rotor rotational speed.
- It can be caused by incorrect manufacturing (nonconcentric outer rotor diameter), rotor thermal bowing, bearing wear and movement or rotor flexible behavior.

**The Maxwell stress tensor**

In order to understand what happen in case of eccentricity, it is necessary to calculate the Maxwell stress tensor. The force per unit of surface which tends to close the gap between two blocks of ferromagnetic materials is defined by the radial component of the Maxwell stress tensor $\sigma_n$, and can be expressed in terms of flux density $B$, whose lines are perpendicular to the airgap surfaces:

$$\sigma_n = \frac{F_n}{S} = \frac{B^2}{2\mu_0} \left[ \frac{V^2 \cdot s^2}{m^4} = \frac{V \cdot s \cdot A \cdot m}{m^4} = \frac{N \cdot m^2}{m^4} = \frac{N}{m^2} \right]$$

In case of a perfectly concentric rotor and stator, these forces act perpendicularly and symmetrically on the rotor and stator surfaces, so that their resultant is null on the overall circumference.
The Maxwell stress tensor

In induction machines, the magnetic flux \( \Phi \) at the airgap is determined by the interaction between the magnetomotive forces produced by the stator and rotor windings and it is proportional to the overall m.m.f. \( M \).

In a simplified explanation of the problem, we can consider these magnitudes linked by the simple relationship:

\[
\Phi = \frac{M}{\mathcal{R}}
\]

where \( \mathcal{R} \) is the reluctance of the magnetic circuit in which the flux \( \Phi \) flows.

Since the reluctance of the airgap is much higher than that of the iron core, the latter is neglected in the approximated calculation of the m.m.f. required to produce a certain flux \( \Phi \).

The main harmonic component of the m.m.f. \( M \) has a sinusoidal spatial distribution at the airgap, with a period depending on the number of pole pairs \( p_p \), and an amplitude which is sinusoidally variable over the time according to the supply frequency \( f \):

\[
M_t(\beta, t) = M_t \cos(\omega t - p_p \beta)
\]

As a consequence, even the amplitude of the main harmonic component of the flux density \( B \) is sinusoidally variable over the time according to the supply frequency \( f \):

\[
B(\beta, t) = \frac{\mu_0 M}{2 \delta} \cos(\omega t - p_p \beta) = \frac{B}{2} \cos(\omega t - p_p \beta)
\]

Therefore, the radial force due to the Maxwell stress tensor has a component which is sinusoidally variable over the time with twice the supply frequency (even in case of uniform airgap).
The Maxwell stress tensor

For this reason, the main frequency of the stator case vibration is twice the supply frequency $2f$ (100 Hz in Europe), even when rotor and stator are perfectly concentric each other.

By integrating the Maxwell stress tensor throughout the airgap, a null resultant is obtained, both in horizontal and vertical direction:

$$F_x = \int_0^{2 \pi} \frac{B_x^2(\beta, t)}{2 \mu_0} \cos \beta d\beta = 0$$

$$F_y = \int_0^{2 \pi} \frac{B_y^2(\beta, t)}{2 \mu_0} \sin \beta d\beta = 0$$

This is valid in case of perfect symmetry between rotor and stator.

Let’s see what happens when the rotor and stator are not concentric (skipping some passages of the demonstration).

Effect of static eccentricity on vibrations

In case of static eccentricity, the flux density is given by the interaction of three harmonics with different number of pole pairs.

Example of approximate distribution of the flux density $B$:

In case of static eccentricity, by integrating the Maxwell stress tensor throughout the airgap, a non-null resultant in the direction of the minimum airgap is obtained: the steady Unbalanced Magnetic Pull (UMP).

Besides, it can be proven that static eccentricity produces an additional component of the radial force (with respect to the concentric rotor condition) which sinusoidally varies over the time with twice the supply frequency.

Therefore, a vibration increase at $2f$ (100 Hz, if the supply frequency is 50 Hz) can be expected in presence of static eccentricity.

Static eccentricity

In case of static eccentricity, the airgap length is given by:

$$\delta(\beta) = \delta \cdot (1 + E \cos \beta)$$

But in the expression of the flux density there is the inverse of $\delta$, therefore the calculation becomes quite complicate. It is possible to demonstrate that the result is:

$$B(\beta, t) = B_1 \cos(\omega t - p_p \beta) + B_2 \cos(\omega t - (p_p - 1)\beta) + B_2 \cos(\omega t - (p_p + 1)\beta)$$

a component with $p_p$ pole pairs, as in case of concentric rotor

a component with $(p_p - 1)$ pole pairs

a component with $(p_p + 1)$ pole pairs

Effect of static eccentricity on vibrations

Example of approximate distribution of the flux density $B$:

Corresponding distribution of the radial force (proportional to the square of $B$):

UMP = Unbalanced Magnetic Pull
Dynamic eccentricity

In case of dynamic eccentricity, the distribution of the airgap rotate at the rotational speed of the rotor \( \Omega \), therefore the length of the airgap can be expressed as:

\[
\delta(\beta, t) = \delta \cdot (1 + E \cos(\beta - \Omega t))
\]

Dynamic eccentricity produces a magnetic rotating force (rotating UMP) at the rotational rotor speed \( \Omega \) (frequency \( f_r \)), which is added to the centrifugal force due to the mechanical unbalance (at the same frequency).

Effect of eccentricity on vibrations

By using the expression of the airgap length in presence of dynamic eccentricity, it is possible to calculate the flux density \( B \), similarly to the case of static eccentricity, and hence the Maxwell stress tensor, which is proportional to the square of \( B \).

In this way, it can be found that dynamic eccentricity also produces vibrations at the following frequencies (sidebands around the fundamental):

\[
2f_s - f_r, 2f_s + f_r
\]

By summarizing, for the induction motors it has been proven that the amplitude of the vibration harmonics at frequencies: \( 2f_s, f_r, 2f_s \pm f_r \)

- rapidly increases with both static and dynamic eccentricity, especially at no-load;
- static eccentricity has only a slight influence on the component at \( f_r \), which, on the other hand, is caused by both the rotating UMP and the mechanical imbalance (both arising from dynamic eccentricity).

MCSA to detect rotor eccentricity

Regarding the MCSA, for the induction motors it has been proven that the amplitude of the current harmonics at frequencies: \( f_s \pm f_r \)

- is strongly dependent on the degree of both static and dynamic eccentricity;
- the effect of the dynamic eccentricity increases from the full load operation to the no-load condition.

Further current harmonics at frequencies which depends also on the number of rotor slots have been proposed to detect rotor eccentricity and proven to be function of the combination of static and dynamic eccentricity.

Short circuits in stator winding supplied at low voltage (LV)
Short circuits in stator winding supplied at LV

Short circuits in stator winding can occur:
1) between turns of the same phase (turn-to-turn);
2) between turns of different phases (phase-to-phase);
3) between turns and stator core (phase-to-ground).

1) Short circuit between turns of the same phase:
2) Short circuit between different phases:
3) Short circuit between turns and stator core at the end of the slot:

Generally, a stator winding insulation failure begins with a short circuit between turns that involves few turns within the same coil.

With a turn-to-turn short circuit, the motor can continue to run, but for how long?

This short circuit generates a high circulation current in the short circuited turns, which causes localized heating and favours a rapid diffusion of the fault to a greater section of the winding.

If not detected, the fault between the turns can propagate and cause phase-to-phase or phase-to-ground failures.

With phase-to-phase or phase-to-ground short circuit, the motor cannot operate and the protective devices disconnect it from its power supply.
Diagnostics of short circuits at LV

In low-voltage machines, the time between a turn-to-turn short circuit and a phase-to-phase or phase-to-ground short circuit can take few minutes or few hours, depending on the severity of the fault and on the motor load. So this is a quickly progressive fault!

To avoid phase-to-phase or phase-to-ground short circuits in low-voltage machines, the only solution is to detect the turn-to-turn short-circuits by means of an online diagnostic technique.

For LV machines, many manufacturers and operators argue that there is no diagnostic tool that is worth being used to detect turn-to-turn short circuits: their idea is that, if a motor starts to fail, it will continue to work until it will breakdown and therefore it will be substituted. But this principle could be valid only if the failure of the motor will not damage the rest of the system and if there is a spare part of the same motor immediately ready to start to work.

In fact, in some cases, an unexpected failure of a low power LV motor can be very expensive or can cause serious safety hazards. Therefore, even for LV machines, it may be useful to develop a diagnostic tool that allows to early detect a short circuit, in order to plan in advance the replacement of the machine and to avoid more heavy failures.

The literature on this subject has identified as possible indicators of stator short circuits for LV machines:
- the stator current (MCSA), which can be measured by means of a non-invasive instrument as a current probe;
- the stray electromagnetic flux around the motor, which can be collected by means of an external flux sensor.

It is important to observe that, among the on-line diagnostic techniques which can be employed to early detect a potential short circuit in a winding of an electrical machine, there is a clear distinction between:
- the MCSA, to detect inter-turns short circuits in Low Voltage (LV) induction motors (rated voltage < 700 V);
- the partial discharge monitoring, to diagnose the ground insulation degradation in High Voltage (HV) electrical machines (≥ 700 V).

Note that, under sinusoidal power supply, the insulation systems of LV electrical machines (< 700 V) are not subject to partial discharges. Nevertheless, partial discharges can happen when LV motors are supplied by inverter.

There are commercial flux sensors which can be used together with (or instead of) current probes: Both types of sensors must allow the frequency analysis of the acquired signals. Further custom flux sensors can be realized in laboratory.
Characteristic frequencies proposed for the diagnostics of the stator short circuits by means of current and stray flux analysis

<table>
<thead>
<tr>
<th>Author</th>
<th>Characteristic frequencies</th>
</tr>
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<tbody>
<tr>
<td>Penman et al.</td>
<td>$f_s \left( k \pm n \frac{1-s}{p} \right) = kf_s \pm nf_s $</td>
</tr>
<tr>
<td>Stavrou et al.</td>
<td>$f_s \left( N_r \frac{1-s}{2p} + 2 + 1 \right) $</td>
</tr>
<tr>
<td>Thomson</td>
<td>$f_s \left(n \frac{1-s}{p} \pm k \right) = nf_s \pm kf_s $</td>
</tr>
<tr>
<td>Henao et al.</td>
<td>$f_s \left( N_r \frac{1-s}{p} \pm \nu \right) $</td>
</tr>
<tr>
<td>Cruz and Cardoso</td>
<td>$3f_s $</td>
</tr>
<tr>
<td>Romary et al.</td>
<td>$15f_s , 17f_s $</td>
</tr>
</tbody>
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$k = \text{odd integer positive number (} k = 1, 3, 5, \ldots \text{)}$

$n = \text{integer positive number (} n = 1, 2, 3, \ldots 2p-1 \text{)}$

$\gamma = \text{integer positive or null number (} \gamma = 0, 1, 2, 3, \ldots \text{)}$

$\nu = \text{harmonic index of the stator current} $
Analysis in the time domain of current and flux

At the top: stator current.
At the bottom: stray flux.
The stray flux shows greater distortion when the fault is present.
In this case, the analysis in the time domain is sufficient to detect the fault.

Analysis in the frequency domain

At the top: healthy. At the bottom: faulty.
The current seems not sensible to the fault.
The two stray flux spectra are very different: the fault is identified by the increase of the harmonics at 150 Hz (3f) and 450 Hz (9f).
These are the normalized spectra during the operation at rated load, with the healthy motor: the number of excited harmonics increases.

It has been observed that, when short circuit is present, the rotor speed decreases, as the electromagnetic torque produced by the motor decreases.

During the operation at rated load, the number of excited harmonics increases (even in the healthy motor) and the fault detection becomes more complex.

In general, this technique seems quite easy to implement, with low cost tools. It looks promising for industrial applications, as it is non-invasive and does not require any particular precaution for its installation.

Nevertheless, the effectiveness of this diagnostic technique in industrial applications to detect short circuits in low voltage motors has still to be proven. Moreover, it is necessary to evaluate the economic convenience of the application of this technique for each particular case.
Bearing faults

Bearing faults can happen due to the following main causes:

- Normal fatigue (wear and tear);
- Contamination (airborne dust, dirt or any abrasive substance);
- Improper lubricant or poor lubrication;
- Corrosion (corrosive fluids or corrosive atmosphere);
- Shaft voltage (bearing currents);
- Excessive load;
- Misalignment;
- Overheating.

Most of these causes (but not all) arouse slowly progressive bearing faults!

Periodical vs. predictive maintenance

For this reason, the common practice to detect bearing faults in low voltage motors is a combination of:

- a periodical condition monitoring of the motors, in which expert technicians collect and elaborate vibration measurements by means of sensors, normally not permanently installed on the machines;
- a periodical preventive substitution and/or lubrication of the bearings after a given number of hours indicated by the manufacturer.

This periodical maintenance is generally effective, but:

- it is expensive and normally needs the employment of personnel and instruments external to the firm;
- it can require early unnecessary substitution of bearings;
- it can fail in case of quickly progressive faults, as those due to shaft currents caused by electronic converters.

Periodical vs. predictive maintenance

For these reasons, over recent years, many studies have been focused on the implementation of a predictive condition monitoring scheme able to detect bearing faults in their incipient stage by means of online continuous measurement and analysis of variables easy to collect, non-invasive and low cost:

- vibration, well consolidated methodology for these faults
- current,
- stray flux.

This detection scheme needs to categorize bearing faults into two main groups:

- single-point defects (cyclic);
- generalized roughness (non-cyclic).

Effects of single-point defects on vibrations

A single-point defect produces an impact between the ball and the raceway and generates detectable vibrations at predictable frequencies $f_r$, which depend on:

- surface of the bearing which contains the fault (outer race, inner race, ball, cage);
- geometrical dimensions of the bearing;
- rotational speed of the rotor $f_r$.

The theoretical frequency to monitor in the vibration spectrum to detect a fault in the outer race is:

$$f_o = \frac{N}{2} f_r \left(1 - \frac{d}{D} \cos \alpha \right)$$

where:

- $N =$ number of rolling elements (ball or roll)
- $d =$ diameter of the rolling element
- $D =$ bearing pitch diameter
- $\alpha =$ ball contact angle, which is equals to 0° for deep-groove ball bearings.
Effects of single-point defects on vibrations

To detect a fault in the inner race:

\[ f_i = \frac{N}{2} f_r \left( 1 + \frac{d}{D} \cos \alpha \right) \]

For a defect in the rolling elements:

\[ f_b = \frac{D}{2d} f_r \left( 1 - \left( \frac{d}{D} \right)^2 \cos^2 \alpha \right) \]

For a defect in the cage:

\[ f_c = \frac{1}{2} f_r \left( 1 + \frac{d}{D} \cos \alpha \right) \]

For simplicity, the outer and the inner race characteristic frequencies can be approximated for most bearings by:

\[ f_o = 0.4 \cdot N \cdot f_r \quad f_i = 0.6 \cdot N \cdot f_r \]

Vibration analysis for single-point defects

Example of vibration analysis in the frequency domain (inner race fault):

\[ f_r = \frac{N}{2} f_r \left( 1 + \frac{d}{D} \cos \alpha \right) \]

MCSA to detect bearing faults

The relationship between the bearing vibration and the stator current of an induction motor can be determined by remembering that any airgap eccentricity produces an asymmetry in the flux density at the airgap.

In turn, this asymmetry affects the inductances of the machine which determine the harmonics of the stator current.

Since rolling bearings support the rotor, any bearing defect produces a radial displacement between rotor and stator.

Therefore, the radial motion produced by a single-point defect arouses stator current components at predictable frequencies \( f_p \):

\[ f_p = \left| f_s \pm kf_v \right| \quad f_v = \text{supply frequency} \]

where \( f_v \) is one of the characteristic vibration frequencies to detect a single-point defect and \( k = 1, 2, 3, \ldots \)

MCSA to detect bearing faults

Since 1995, many studies have been focused on the possibility to employ the motor current signature analysis (MCSA) as an alternative diagnostic index for bearing faults, with respect to the vibration measurements.

After 2006, even the external stray flux has been considered with the same purpose.

**Generalized roughness**

Generalized roughness is a very common fault in rolling bearings, but it has not been sufficiently considered in the literature. Since generalized roughness is not a single-point defect, the characteristic fault frequencies are not expected to be excited and their monitoring could be ineffective to detect this fault.

Only few studies have been dedicated to discover a generalized roughness by means of MCSA and very few by means of the stray flux analysis.


**MCSA to detect generalized roughness**

In our laboratory, we have tried to diagnose the presence of generalized roughness by means of the analysis of both the current and the stray flux signals.

Previously, we have examined other bearing faults by means of the analysis of current and stray flux, but considering only the harmonics multiple of the fundamental.

Then, we have decided to pay attention also to the characteristic harmonics derived from the equations of the single-point bearing defects.

**The test-bench**

The bearing faults have been simulated on a three-phase induction motor, $P_n = 2.2$ kW, 2 poles, $n_n = 2800$ rpm, supplied by the mains (400 V, 50 Hz) and joined with a magnetic powder brake.

The ball bearings are double-crown, with a plastic cage which allows a simple disassembly of the balls. **Generalized roughness** was artificially created on all the balls of a bearing, at three progressive stages, by immersing the balls in a solution of concentrated sulfuric acid.

Therefore, four conditions of the bearing are available:
The experimental tests

The motor was tested in 8 different cases (GC1, GC2, ... GC8): two cases (at no-load and at 75% of the rated load) for each condition of the bearing.

In the faulty cases (from GC3 to GC8), the drive-end bearing of the motor was substituted with one of the artificially damaged bearings.

In order to obtain a robust diagnosis from a statistical point of view, for each case, a set of 40 acquisitions was collected: each acquisition consists of 2\(^{19}\) samples, gathered with a sampling frequency of 20 kHz.

In each acquisition, 3 variables have been measured in a synchronous way:

a) current of one phase;

b) axial leakage flux, by means of a commercial probe;

c) radial leakage flux, by means of a custom probe.

Each acquisition has been transformed in the frequency domain, in the range 0\(-\)2000 Hz.

The mean and the standard deviation of the 40 spectra related to each set of acquisitions have been calculated.

The mean of the spectra related to each healthy case has been compared with the corresponding faulty cases.

We decided that the warning of possible fault is present when an excited harmonic appears within a range of \(\pm 5\) Hz around each characteristic frequency of fault. This “range of sensitivity” permits to overcome possible misunderstandings due to measurement errors or to small changes in the mechanical speed of the rotor, in order to make more robust the fault detection in industrial environment.

The experimental results

In the following tables, the characteristic frequencies of the single-point bearing faults are reported, when the related harmonics reveal a difference in amplitude between the healthy and the faulty cases higher than three times the standard deviation of the healthy case.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Variable</th>
<th>Characteristic harmonics (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC3 vs. GC1</td>
<td>Current</td>
<td>640</td>
</tr>
<tr>
<td></td>
<td>Emerson flux</td>
<td>540, 640</td>
</tr>
<tr>
<td></td>
<td>Custom flux</td>
<td>930, 1030</td>
</tr>
<tr>
<td></td>
<td>Current</td>
<td>300, 540, 1400, 1500</td>
</tr>
<tr>
<td>GC4 vs. GC2</td>
<td>Emerson flux</td>
<td>30, 300, 400, 440, 520, 540, 640, 930, 1030, 1425, 1525</td>
</tr>
<tr>
<td>75% load, step 1</td>
<td>Custom flux</td>
<td>300, 400, 440, 520, 540, 930, 1030, 1425, 1525</td>
</tr>
<tr>
<td>GC5 vs. GC1</td>
<td>Current</td>
<td>185</td>
</tr>
<tr>
<td>no-load, step 2</td>
<td>Emerson flux</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Custom flux</td>
<td>---</td>
</tr>
<tr>
<td>GC6 vs. GC2</td>
<td>Emerson flux</td>
<td>30, 520</td>
</tr>
<tr>
<td>75% load, step 2</td>
<td>Custom flux</td>
<td>540</td>
</tr>
<tr>
<td>GC7 vs. GC2</td>
<td>Current</td>
<td>70, 285, 300</td>
</tr>
<tr>
<td>no-load, step 3</td>
<td>Emerson flux</td>
<td>30, 70, 90, 170, 185, 285, 300, 400, 420, 440, 520, 540, 640, 670, 770, 930, 1030, 1400, 1425, 1500, 1520, 1910</td>
</tr>
<tr>
<td></td>
<td>Custom flux</td>
<td>5, 30, 70, ..., 170, 185, 285, 300, 400, 420, 440, 520, 540, 640, 670, 770, 930, 1030, 1400, 1425, 1500, 1520, 1910</td>
</tr>
<tr>
<td>GC8 vs. GC2</td>
<td>Emerson flux</td>
<td>300, 520</td>
</tr>
<tr>
<td>75% load, step 3</td>
<td>Custom flux</td>
<td>30, 185, 285, 300, 400, 420, 440, 520, 540, 640, 670, 770, 930, 1030, 1400, 1425, 1500, 1520, 1910</td>
</tr>
</tbody>
</table>
The experimental results

Observations:
- The \textit{stray flux} presents a more consistent diagnostic content with respect to the stator current, so its use as diagnostic indicator seems promising;
- The frequencies highlighted in bold are common to almost all the examined cases;
- The characteristic frequencies of the single-point bearing defects seem significant also in case of generalized roughness, provided to neglect the selectivity of the damaged component;
- The analysis of these frequencies has to be completed with the monitoring of the trend of all the harmonic spectrum;
- The detection ability of the \textit{custom flux probe} seems more effective with respect to the commercial flux sensor.

Differences between the means of the spectra of the \textit{custom flux} related to the cases GC1 and GC3 (no-load, \textbf{step 1}): 

Differences between the means of the spectra of the \textit{custom flux} related to the cases GC1 and GC5 (no-load, \textbf{step 2}): 

Differences between the means of the spectra of the \textit{custom flux} related to the cases GC1 and GC7 (no-load, \textbf{step 3}): 

Note that, when the motor is supplied by inverter, the fault detection by means of the stator current and stray flux analysis becomes more complex, since the electromagnetic signals are more “dirty” and disturbed by the harmonics introduced by the inverter (specific algorithms for filtering the signals are needed).
The experimental results

A thermal analysis can help in detecting a bearing fault (the dimension of the “red area” increases with the damage degree):

Healthy

Damage step 1

Damage step 2

Damage step 3

Thank you very much for your kind attention!

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