Different approaches to the preventive maintenance of induction motors

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Abstract

The paper explains various approaches available in practice for the prediction of faults inside a motor from external measurements and observations. The advantages and drawbacks are compared and indications are provided of the amount of work involved. The emphasis is on methods preferably requiring measurements not interfering with the normal operation of the machine. Winding short-circuits, broken rotor bars and bearing problems are the most important reasons of failure of induction motors. For short-circuits rapid actions have to be taken to avoid further damage. Induction motors can work with one or several broken rotor bars during a longer period. However, in order to avoid increased rotor damage by overloading the intact bars, the rotor has to be repaired as soon as possible. Bearing problems are to be cured when noticed. Four types of signals are discussed: vibration measurements, shaft fluxes, stator current and temperature.

Keywords:

Winding short-circuits, broken rotor bars, bearing problems, on line monitoring, preventive maintenance

Introduction

The scope of the paper is the monitoring and protection of low voltage induction motors with squirrel cage rotors. The squirrel cage induction motor is a marvel of mechanical simplicity, though its operating principles are subtle and sophisticated. These motors use neither brushes nor wound rotors and therefore, it may be expected that they are robust and reliable. These polyphase induction motors are common prime movers. Using power electronics, their penetration into the drive market increases steadily.

While they are extremely reliable machines, they do suffer degradation and occasional failure. These relative inexpensive ac motors are often condition monitored, not because of interest in the motor's well-being, but out of concern for the machine driven by the motor or for the process it participates in. Induction motors perform very essential functions in manufacturing processes. Therefore, the costs resulting from their failure often are much higher than the actual cost of the motor [1-8].

While replacement or refurbishment of a squirrel-cage motor is relatively inexpensive, the cost of unexpected process cessation is not. In modern systems, preventive maintenance procedures are used to avoid the non predicted breakdown of induction motors. This should result in the possibility of repairing or replacing the motor during scheduled stops or during normal stand still periods.

The paper explains various approaches available in practice for the prediction of faults inside a motor from external measurements and observations. The advantages and drawbacks are compared and indications are provided of the amount of work involved.

It should be stressed that developments have been reported incorporating flux measurements in the machine air-gap [9]. However, they are only feasible in new installations or during rewinding processes and therefore, have a limited scope.

General considerations

The most common faults occuring in squirrel-cage induction motors are bearing, stator and rotor faults (Table 1) [10,11]. A monitoring system has to distinguish between the various faulty conditions correctly. Disruptions of the rotor circuit for instance give rise to torque and speed pulsations and vibrations often mistakenly assigned to other mechanics such as unbalance or driven-machine deficiencies.

Table 1 Common induction motor faults

Bearings	41 %
Stator	36 %
Rotor	9 %
Remaining	14 %

Causes of early motor deficiency are multiple and motor lifetime is limited. A motor is designed to operate during 25.000 hours at rated load. It is the general feeling of maintenance engineers that this is much longer in practice. As explained further on, this is almost always so. Causes for early breakdown are split into four categories.

- Wrong rated power yielding overheating and ageing of the stator winding and/or bearing failure.
- Motor surroundings. At the electrical side the voltage may be too high or too low, the rotation speed may be wrong, Y or Δ-connection has to be correct. When using frequency inverters, the motor parameters have to be appropriate: a CSI requires a low leakage inductance while a VSI prefers a high leakage inductance. Sufficient cooling air has to be available at an appropriate temperature. The driven load has to be in line, well balanced and protected not to overload the motor.
- Misuse of the motor. Examples are a wrong speed (too high or too low supply frequency in inverter drives, staying in a forbidden speed zone causing resonance); too high load, a too large number of start/stops or a wrong starting/stopping procedure, none or not enough maintenance.
- Mistakes during repair (wrong winding, wrong bearing choice, ...). A number of tests should be carried out before reinstalling the machine.

Although a good monitoring system may assist in assessing all of the problems mentioned above, it will be assumed that the motor is correctly chosen and that no initial faults are present at installation or after repair.

There are many and varying approaches and devices for motor protection available on today's commercial market. Classically, motor protection equipment is typically aimed at protecting the motor insulation against overheating. Further protection can be gained by applying equipment based on sensing vibrations and/or current spectra of the motor to predict incipient failures. Other approaches try to avoid insulation overheating while sensing or estimation the temperature in the machine. Shaft fluxes and shaft voltage have also gained attention.

Although this is not fully correct for the temperature sensors used in monitoring systems, all other methods discussed here do not require any interference with the motor operation and may be brought in after the motor is installed in the manufacturing process. They monitor the motor during normal operating conditions and do not require the machine to be switched off. In general terms, a motor monitoring and protection device should work with any motor design and load condition, on line with no more than the nameplate data input, and with a high degree of accuracy. In other words, a resident expert is not required.

Vibration measurements

Signal transducers

Vibration measurements have proven capable of detecting many problems in electrical machines [12-15]. Although this technique requires a lot of skills and careful thoughts, the advantage is that a lot of the preventive maintenance and monitoring work is done by mechanical engineers, who are far more familiar with mechanical measurements and their interpretation than with electrical measurements and their indirect link with mechanical problems. Furthermore, the vibrations measurement equipment is often already available as they are required also for monitoring other rotating devices as pump, fans, turbines, etc.

Piezo-electric vibrations transducers are most common, and are mounted on the surface of the machine. Monitoring measurements are most frequently taken from radially oriented accelerometers. This is not optimum for many electromagnetically linked faults as the fundamental mechanical reaction to electromagnetic faults is a torque, not a radial force. Tangential orientation of an accelerometer, particularly horizontal at the top of a foot-mounted motor, offers a better opportunity to sense the reactions to these torques.

The mounting of the accelerometers has to get very much attention. A lot of possibilities exist. The most simple is to mount the accelerometer on a pen and to push it to the motor surface. Although this seems to be very elementary, it has the advantage of being extremely simple and no special precautions have to be taken. The pressure has to be high enough to keep contact between the surface and the pen. The frequency response is limited. This has to be kept in mind: if a component indicating a problem in the motor, has a frequency above of the limiting frequency of set-up, it can not be measured. The second method is to mount the accelerometers using a magnet. The advantage is that the accelerometer is very well oriented to the vibration orientation and has always the same orientation. Mounting is simple and straight forward, although sometimes the surface of the motor has to be prepared. The most common method is to screw the accelerometer to the surface and to put beeswax in between the surface and the accelerometer in order to ensure contact. The frequency range is very wide. Mounting the accelerometer requires a lot of preparation, certainly the first time the motor is taken into a monitoring procedure. A part of the motor surface has to be freed from paint, has to be grinded and then the accelerometer is mounted. This is done for key motors only and the mounting screws are left.

The choice of the accelerometer is also extremely important. The accelerometer has two key characteristics. The first is the cut-off frequency and the second is the sensitivity, this is the output signal per unit acceleration applied to the accelerometer. The higher the accelerometer mass, the lower the frequency range. Larger accelerometer are generally more sensitive. A trade off is thus required. The charge amplifier may be external or built in the accelerometer. The last solution is to be preferred as the sensitivity to external signals is far less. This is particularly important in inverter supplied applications.

Piezo-electric accelerometers have a limited temperature range. When vibration measurements have to be carried out in hot areas, non contracting eddy current probes may give a solutions. They are mounted facing towards the vibrating surface, mostly the shaft. This approach is quite sensitive and as such vulnerable to external interference.

Signal analysis

Recording the overall level is simple, but does not offer a lot of discriminating facilities. If the component, influenced by the fault conditions, is not a large one, the fault has to be very pronounced in order to increase the overall vibration level above a preset value. However, if the particular component is filtered from the signal, the problem is noticed much sooner. The normal way for obtaining a frequency spectrum of the signals is using Fast Fourier Transform by an expensive FFT analyser on the spot or by hand on recorders locally followed by an off line analysis later on. The digitally recorded spectra are very interesting for zooming purposes, particularly important for distinguishing between various vibration sources and thus eventual faults. As trend analysis is the to a reliable machine fault monitoring system, using digital recording systems and massive archiving capabilities, lead to simple and easy comparison methods for signals taken at different instants in time.

Faults and the frequency content

The frequency generated by a specific failure is extremely important. An unbalance gives a 1 times the rotational speed signal. It should be stressed that unlike in most mechanical system, the rotor of an induction machine is heated by the losses. This may cause an unbalance during operation due to a differential thermal expansion. Misalignment and a bent shaft are other common mechanical faults. They lead to vibrations with once (usually), twice (often) and sometimes even 3 or 4 times the speed. Damaged rolling element bearing (ball, roller etc.) lead to vibrations corresponding to the impact rates for the individual bearing components. Also vibrations at very high frequencies may be a result (20 to 60 kHz).

Damaged and worn gears lead to tooth meshing frequencies, this is the shaft speed times the teeth number and their harmonics. Mechanical looseness causes twice the speed vibrations, with smaller components at 0.5, 1.5, 2.5, 3.5 etc. times the speed. Increased turbulence in the fan yields to blade and vane passing frequencies and harmonics.

Electrical faults also lead to mechanical vibrations. A stator asymmetry, either in the supplied voltage, the stator winding or the stator magnetic circuit, yields double supply frequency pulsating torques. A cause for supply asymmetry may be a missing phase. With respect to monitoring the stator winding, a short circuited turn introduces an asymmetry in the m.m.f. and thus leads to double supply frequency vibrations. In the same way, a rotor asymmetry introduces low frequent double slip frequency vibrations. These may be due to a broken bar or a broken ring segment. They can be noticed during a slow start where the motor start to vibrate at double supply frequency and where the vibration frequency decreases as the motor speeds up. In a two pole machine, the static eccentricity leads to double supply frequency lateral vibrations. In a dynamically eccentric machine, double slip frequency vibrations. When an induction motor is supplied with a frequency converter to control the speed, the voltage and current harmonics generate torsional oscillations at six times the fundamental supply frequency and the multiples. Due to the higher switching frequencies, these vibrations are reduced considerably, but are still present. The space harmonics in the machine lead small torsional vibrations.

Table 2 Frequency of the dominant components

Nature of fault	Frequency of dominant vibration
Unbalance	1*rpm (but temperature, thus load dependent)
Misalignment&bent shaft	1*rpm usually 2*rpm often 3&4 rpm sometimes
Damaged rolling element bearing (ball, roller, etc.)	Impact rates for individual bearing components. Also vibrations at very high frequencies (20 to 60 kHz)
Damaged&worn gears	Tooth meshing frequencies (shaft rpm*teeth number) and harmonics
Mechanical looseness	2*rpm 0.5; 1.5; 2.5; 3.5; etc.
Increased turbulence	Blade&vane passing frequencies&harmonics
Stator asymmetry	Double supply
Rotor asymmetry	Double slip
Eccentricity & p=1 Static Dynamic	 Double supply Double slip
Frequency inverter	6*supply & harmonics
Space harmonics N2: number of rotor slots p: number of polepairs s: slip	$f_1\left[2+(1-s)\frac{g_2 N_2}{p}\right]$ g=±1, ±2, ±3, ±4,...

The electromagnetically caused vibrations interfere with a monitoring scheme, often only aiming at mechanical failures Small torsional vibrations due to space harmonics are in the high frequency range interfering with bearing monitoring.

An often used method for discriminating between electromagnetic problems and mechanical problems is to compare the vibrating spectra during normal operation and immediately often switching off the machine. If the speed remains roughly the same, the electromagnetically caused vibrations vanish, while the mechanically caused remain.

Shaft flux measurements

For an ideal machine, the axial flux is zero. Under fault-free conditions, rotor and stator currents are perfectly balanced. In practice asymmetries exist in both circuits due to slight imperfections in winding geometry as well as non-uniformities in the materials of construction. The net effect of these deviations from the ideal machine is to produce a small, but measurable, axial leakage or shaft flux. It is claimed that this technique is capable of detecting:

. broken rotor bars or rotor rings
. stator winding interturn short circuits
. loss of phase
. negative sequence in supply lines
. eccentric running.

This technique is quite tempting as it requires a relatively small effort. All that is needed is a search coil placed concentric with the shaft of the motor, or a series of coils axi-symmetric to the shaft. Typically there is sufficient axial leakage flux so that it is possible to mount the coil or coils external to the machine frame. However, if an iron frame is present, a lot of the axial leakage flux passes via the end shields rather than inducing a voltage in the coil. If the signal is too low, mounting the measuring coil between the bearings and the rotor before installing the machine or during overhaul may solve the problem. Different faults cause different frequency spectrum components to be present in the axial flux. Therefore, measuring the r.m.s. voltage induced in the coils is seldom sufficient.

If there is an asymmetry in the supply, a negative sequence system is present in the stator winding. This leads to rotor currents and axial fluxes having $(2-s)f_1$ as frequency. Eccentricity, both static and dynamic disturb the sinusoidal flux distribution. The airgap length varies as a function of the airgap length. In order to find the influence on the rotor, these expressions have to be transferred to the rotor. For a dynamic eccentricity, a rotor observer sees a constant airgap pattern (time independent), while a stator observer sees a varying airgap length. When a static eccentricity is present, the situation reverses.

Let us take the example as given by Jarzyna [16]. The stator has a four pole winding. The shaft flux is measured for a machine with a 15% static eccentricity with a clear presence of 50 Hz and 75 Hz components in the static eccentricity case. The 25 Hz component is lower, due to the induced voltage principle used to measure the shaft flux (figure 1). With an asymmetrical supply, the presence of the 100 Hz component is clear.

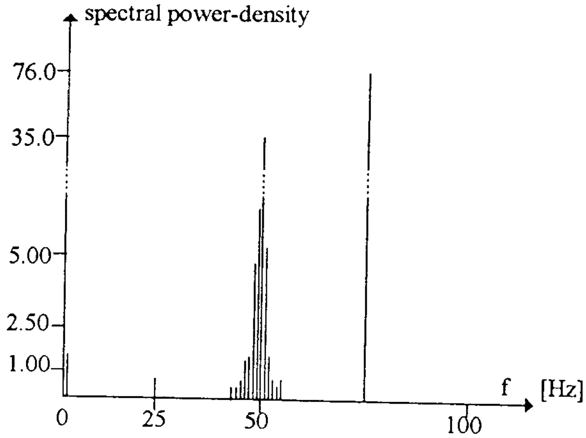

Figure 1. Shaft flux with 15 % static eccentricity

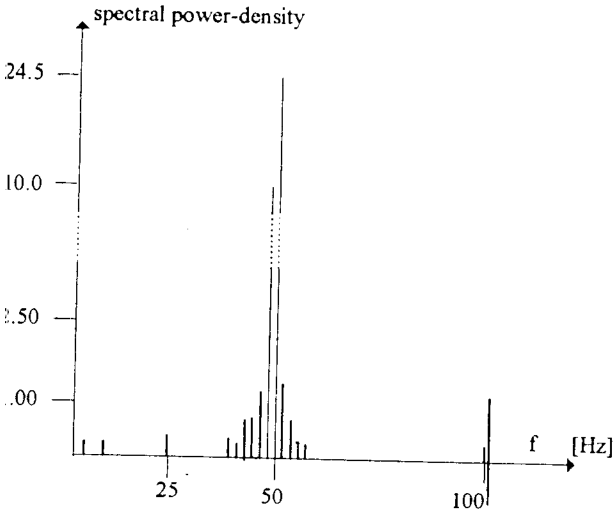

Figure 2. Shaft flux with two-phase supply

he effect of the interturn fault is to remove a turn from ıe stator winding. This has a small, but finite effect on ·e main airgap flux distribution. In addition, an e.m.f. is ıduced in the shorted turn resulting in a current flow lim- ɜd only by the impedance of the fault. The fault current ɹe to the shorted turn is the source of an additional mmf ɹlse, having a space harmonic distribution superposed ı the main field distribution. This leads to a change in e time harmonics observed in the leakage flux. These fects form the basis of the fault identification technique.

easurements as detailed in literature, demonstrate that is both practical and feasible to detect a shorted turn a ator unbalance and eccentricity in a stator winding using relatively simple axial flux leakage measurements. The il used to make these measurements is inexpensive to ild and can easily be retrofitted to most motors. The ectronic circuitry necessary to measure the magnitude the specific harmonics in the axial flux signal is rela- ely simple. However, it should be recognised that this chnique cannot be applied on a single measurement sis, but requires a fingerprint of the flux while no prob- ns are present.

Stator current analysis

large number of induction motor faults give rise to iations in the mutual and self inductances. This gives e to detectable changes in the stator current spectrum -20]. These changes can, however, be obscured by the currents produced by the position-varying load torque. Using appropriate signal processing techniques, several effects may be distinguished, as there are broken rotor bars and eccentricity, and those distinctions can even be made at load.

By detecting these components in the current, it is possible to build a monitoring system that in principle does not require any interference with the drive. Furthermore, it is well suited to be automised using neural network techniques. Special filtering techniques are required to distinguish the small frequency components from the dominant supply frequency.

An eccentric air-gap with a dynamic eccentricity yields the following frequencies:

$$f_{eccentricity} = f_e\left[1 \pm m\left(\tfrac{1-s}{p}\right)\right] \quad (1)$$

(f_e: supply frequency, p: number of pole pairs, s: slip, m= 1,2,3,). A broken rotor bar yields the following frequencies:

$$f_{brokenbar} = f_e\left[\nu\left(\tfrac{1-s}{p}\right) \pm s\right] \quad (2)$$

(ν=6g+1, g=0,$\pm$1, $\pm$2, $\pm$3, ...).

The bearings support the rotor. Each mechanical bearing vibration leads to a radial displacement of rotor and stator. These air-gap variations yield inductance oscillations and thus current changes with frequency:

$$f_{bearing\ problem} = f_e \pm m f_v \quad (3)$$

f_v is one of the vibrating frequencies f_i or f_u, that mostly may be approximated by:

f_i=0,6nf_{rm}

f_u=0,4nf_{rm}

(f_{rm}: mechanical speed [Hz], n=6,7...12 number of balls).

The load induced harmonics are coincidental with rotor fault induced harmonics when the load varies synchronously with the rotor position. Furthermore, since the effect of the load and fault on a single stator current harmonic component is spatially dependent, the fault induced portion cannot be separated from the load portion. Therefore, any on-line diagnosis scheme that measures the spectrum of a single phase current, must rely on monitoring those spectral components that are not affected by the load torque oscillations. With this in mind, the detection of broken rotor bars is still possible since the current typically contains higher order harmonics than those induced by the load.

The main advantage of this approach is that no extra transducers are required. Especially in inverter supplied machines, a current sensor is readily available. Only the analysis equipment has to be installed.

Thermal protection

Most insulation systems used in low voltage motors today are organic in nature and are, therefore, subject to deterioration by excessive heat. The heat is generated in the windings due to current passing through it's conductors and is a function of the square of the current. Also other motor losses contribute to heat and temperature rise.

The insulation materials are subdivided in the so-called temperature classes. A certain temperature class indicates the tolerable temperature rise on top of 40°C ambient temperature. If a motor is correctly designed, used at rated load and installed in a room at an ambient temperature of 40°C, the lifetime is 25.000 hours. An increase of the temperature by 10°C cuts the expected lifetime roughly by halve, while a decrease by the same temperature roughly doubles the lifetime. As motors are certainly part of their time operating at reduced load or as the ambient temperature is not always 40°C, the real lifetime of motors is in most of cases much higher than 25.000 hours. It should also be stressed that a higher insulation class, is no indication whatsoever of an increased expected lifetime.

A first approach is the measurement of the stator resistance. This is a relatively simple measurement to carry-out. It may be performed off-line after switching off the motor. A comparison with the values of prior measurements is required. The temperature has to be assessed as correctly as possible, as a temperature difference of 1 K has a major influence. Attempts have been made to perform these measurement on load by injecting small dc currents into the motor and using the V/A ratio as resistance value.

In three phase systems, the measuring error can be reduced significantly using a comparison between the three phases. In a healthy motor, the three temperatures are the same. If the temperature is different in one of the three phases, a fault may be present.

An accurate and reliable protection scheme for the motor consists of a number of temperature sensors mounted at different points in the winding. Preferably the sensors have to be installed during manufacturing or rewinding. The sensors are installed at the bottom of the slots and in the end windings at the outlet side of the air. Two groups of sensors are used. The first group gives an indication of the temperature, rather than measuring it, NTC (Negative Temperature Coefficient) and PTC (Positive Temperature Coefficient) resistances are examples. They provide a signal when a certain temperature threshold value is passed. Although thermocouples are used, Pt-100 sensors, based on a platina wire with a rated resistance of 100 Ω are the best choice nowadays. An accurate temperature measurement is possible using a Wheatstone type of resistance measuring system. Apart from the accuracy, it should be stressed that many PLC's (Programmable Logic Controllers) already incorporate all Pt-100 auxiliary circuitry, making motor monitoring and protection simple and straightforward.

Instead of using a direct or indirect measurement of temperature, in which the reason for the overtemperature as such is unimportant, thermal models, trying to predict a too high temperature from terminal quantities measurement, this is from the current, have to account for the way the high temperature is generated. In general, excessive heat is related to two regions of motor performance [21]. The first involves transient overloads which occurs between 250% to 1000% of the motor's full load current. Transient conditions include motor starting where the motor draws the starting current for almost the full acceleration time, motor stall where the motor has insufficient torque to accelerate the load, and motor jam where a sudden mechanical jam causes the motor to stop or to stall. The high current values during a short time lead to a quasi adiabatic heating of the machine winding as the time constant of the copper mass is much lower than the time constant of the iron. Therefore, the limiting temperature in the motor's winding occurs within few seconds, typically less than halve a minute.

The second region involves running overloads. In this condition the motor is always running, thereby providing some cooling action causing a gradual increase in the winding temperature. The winding is in thermal equilibrium with the iron and the time constants involved are much longer. Running overloads occur in the range from 1 to 2 times the motor's full-load current.

The first step in a realistic motor protection solution is to model the thermal performance. The model should emulate the thermodynamic behaviour of the motor's stator and rotor under steady and transient state conditions, including heat transfer from motor's windings to the iron and from there to the housing and to the free air. The motor model should take into account the important differences in the thermal behaviour due to the motor size and type of construction. The latter is closely linked to the so-called IP classes (Index of Protection) indicating the possibility of particles and moisture to get into the motor.

Once a satisfactory model is derived, system inputs such as currents and starting time, can drive the model. The motor model calculates the winding and the rotor temperatures and compares them with allowable temperature limits. If the temperature limits are exceeded, the motor trips off line. Under running transient conditions, such as mechanical jam, the sudden change of r.m.s. current is compared to a selected dI/dt value and the motor trips off line if this value is exceeded.

On figure 3 an example is given. In this scenario the motor starts for 5 seconds and then runs at full load current for approximately 2200 seconds. The motor is then subjected to a running overload condition raising the temperature to the maximum allowable temperature, resulting in an overload trip. After a forced cooling down period to bring the winding temperature to a safe level, the motor starts and runs at full load current until the winding temperature stabilises. Note the very fast rise of the rotor temperature when the motor is started. However, under running overload conditions, the stator temperature rate of rise is higher than the rate of rise of the rotor temperature.

Two warnings have to be issued. Although resistances measurements may give an accurate temperature value, it is only the average value of the winding temperature. Hot spots cannot be predicted, although they are the reason for winding breakdown. Thermal models may be dangerous as they can not account for external factors as blocked cooling air inlet, high temperature of the cooling air and increased temperature of the motor surroundings.

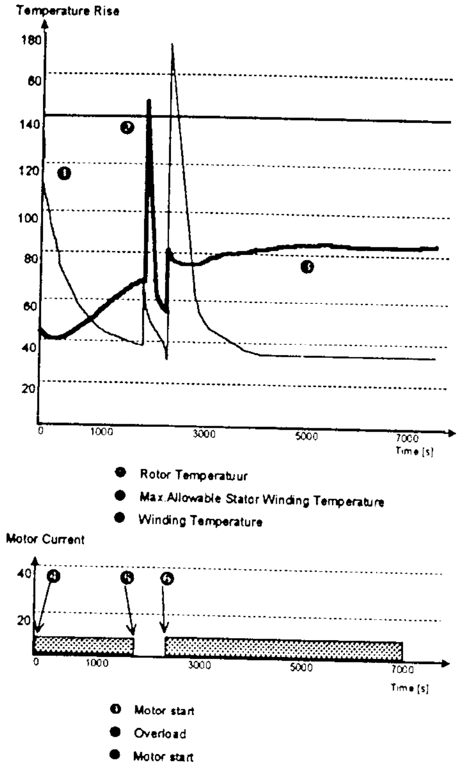

Figure 3 Temperature rise as a monitoring tool

Conclusions

As a conclusion, it should be clear that none of the approaches is the best. Vibration monitoring still is the most versatile and allows the best discrimination between the different faults. However, it requires quite a lot of skills and is expensive with regard to measuring equipment. Electrical problems are difficult to retrieve amongst the other problems due to non -electric causes.

Shaft flux measurements do not offer a lot of possibilities as the signal is not very discriminating. The installation of flux sensing devices during the motor manufacturing or rewinding is far better, but has the disadvantage that the coils are mounted inside the machine.

The current analysis is very promising. Emphasis has to be placed on the correct signal analysis and interpretation. From the sensor point of view, the approach is very interesting as no additional current measuring equipment has to be installed in inverter supplied applications.

Temperature measurements when correctly performed using direct sensors is both reliable and relatively inexpensive. It only protects the stator winding as such.

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