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## OPERATIONAL NON-CONTACT DIAGNOSTICS OF INDUCTION MACHINE BASED ON STRAY ELECTROMAGNETIC FIELD

*Paper deals with one new method of testing and operational diagnostics of induction machines using a stray electromagnetic field. This leakage field on the surface or on surroundings of machine frame is the carrier for diagnostic information and we can make simultaneous comparisons of utility, advantages and disadvantages of the existing and most common methods of diagnostics performed using the measurement of the machine supply current. This method is patented as Czech Patent CZ 303 470, UPV 2012.*

**Keywords:** Induction machine, asynchronous motor, functional testing, technical diagnostics, frequency spectrum, current spectrum, stray electromagnetic field, leakage electromagnetic field.

### 1. Introduction

Operational diagnostics of electric machinery represents a field of diagnostics using information associated with operating values of particular machinery to draft final diagnostic results [1 and 2]. Historical development of asynchronous machinery as the most common type of rotary machines in general is fairly long and headed towards a definite objective - maximum utilization of particular design assemblies. That makes the current machinery substantially less bulky and lighter while their mechanical and electrical parameters have improved [3 and 4]. Manufacturers strive to comply with the laws of economics to deliver their production at the minimum cost possible; users pursue the same reasons and seek for the cheapest equipment with the best reliability and durability characteristics feasible [5]. The main objective of technical equipment must not always lie in the maximum reliability, this is due to various reasons (mostly economic or the so called "environmental" ones nowadays), the equipment may show threshold values for utilization of certain materials in particular assemblies rising the potential breakdown risk of particular components, which may lead to numerous alternatives and serious consequences [6]. This further emphasizes the significance of technical diagnostics that may eliminate some deficiencies to a certain extent in a suitable manner to help the equipment operators increase the reliability of their machinery as well as the entire system, where it is integrated. Economic objectives followed by the operator can therefore be met at a much higher level [7].

### 2. Asynchronous machine as a mechanical/electric system

Asynchronous machines are ranked among electric rotary machinery, the potential breakdown risks are then based on the machine layout as well as the relevant design and operating assemblies comprising the following:

- Electric circuits – i.e. machine wiring with the relevant accessories (conductors, insulating system, outlets and terminals)
- Magnetic circuits of stator and rotor
- Mechanical parts, especially a shaft and bearings, frame, vent.

Reliability of certain assemblies of particular machines can be determined either by analytical or model means, even the so called defect records (defect analysis log - breakdowns and causes) kept at servicing organisations can be a fairly accurate source of data.

Statistics show that electric circuit tends to be the part of machinery most prone to breakdowns; it is mainly the insulating system of stator wiring and the integrity of rotor wiring, which corresponds to the load exerted on these components and potential risks arising from their design. Failures of electric circuit bring fatal impact on machine operability and result in serious interference with all the operating characteristics and values of machinery even when in "smaller" extent (torque, noise, vibrations, temperature increase).

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Failures of electric circuit are less common, these are mainly caused by another defect in the electric or mechanical system of the machine. This type of failure is often due to incorrect maintenance. Failures of the electric circuit would mostly have a low impact on the overall machine characteristics only, as the machine generally remains operable even in such case.

The statistics also show that most breakdowns would not occur individually, several of those are mutually linked in terms of contingencies, some of which may be causative. Diagnostics and servicing of machinery must be based on clear knowledge of these contingencies to ensure accuracy of conclusions reached by diagnostics and correct servicing outcome. This event would result in repeated occurrence or further development of the same or similar failures.

To achieve a clear diagnosis, the particular diagnostic value must be free from any impact brought by changes inside the machine irrelevant to the initial change of conditions or failure or to create an opportunity to confirm or refute such impact using another method or value. One of the options to describe the method for obtaining diagnostic information comprises a detailed analysis of the energy flow inside machine, i.e. a procedure following genuine physical basic principles of the machine operation in relevance to all the physical processes taking place inside the machine in operation.

Rotary electric machine operates with dominant energy flow (depending on the machine operation mode) along the power supply axis (current supply) and the machine shaft (mechanical work). Electric circuits integrated within are defined by the design and type of machine to control the energy flow – wiring, magnetic circuits and air gap. Electromagnetic field plays a key role in transmission of energy between the stator and rotor, Fig. 1.

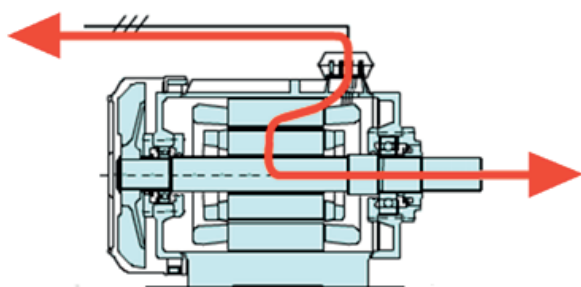


Fig. 1. Dominant way of energy transformation in asynchronous machine as motor or generator

The energy flow through the machine is subject to several effects, some of which are parasitic. The background of dominant transformation of energy is abound with various events, some of which affect the flow of energy. This impact is generally periodic and off the sequence of essential harmonic frequencies. Focusing on any design or failure asymmetry, for example, will reveal its distortion effect on energy flow in the machine

by characteristics means. Such distortion will then produce a characteristic projection into other operation values. When proven by measuring or even changed by further electric or mathematical alteration of the signal produced, the distortion can be separated from the main energy flow to obtain the actual diagnostic value required as the information leading towards diagnosis.

### 3. Diagnostic methods based on frequency analysis of operation parameters of asynchronous machine

Our laboratory has been dealing with development or improvement of diagnostic methods applicable to asynchronous machines for several decades. Research activities conducted by our team have been always aimed at simple obtaining of diagnostic values and applicability of methods even under complex conditions (hazardous areas, e.g. mining environment). The most common failure is represented by breach of rotor cage bars resulting in infringement of symmetry in rotor circuit proven by contravention of current density in particular bars – rotor phases – with subsequent change to the course of electromagnetic field along the rotor perimeter. The rotary field of machine will develop new fields the rotary speed of which is no longer synchronous and these cause cyclic distortion of the main field. The distortion is further transferred via field distortion inside the air gap to enter the stator field to affect the course of current fed to the machine. The main harmonic will be accompanied by lateral bands – frequency lines in reflective layout corresponding to the machine slip frequency:

$$f_x = f_1 (1 \pm 2s) \quad (1)$$

Where:  $f_x$  - is the frequency of lateral bands expressing asymmetry,  $f_1$  - is the frequency of machine supply voltage ("i.e. the first one – dominant harmonic"),  $s$  - is the slip.

Our measurements have proven direct proportion between amplitudes of these characteristic frequencies and the supply frequency and the magnitude of failure; this ratio can therefore be employed as a diagnostic value to determine presence of asymmetry and for optional benchmark measurements to define the extent of asymmetry. Any asymmetry of machine will show the current spectrum with further - the so called speed - frequencies to be derived using our formula below:

$$f_n = \frac{n}{60} + s \cdot f_1 + i \frac{n}{60} \quad (2)$$

Where:  $n$  - is the machine shaft revolution per min.,  $f_1$  - is the supply voltage frequency,  $n_s$  - refers to synchronous speed. Further frequencies present within the machine current are generated by fluting of stator and rotor slots and potential mechanical asymmetry – most often eccentricity:

Stator slots frequency:

$$f_v = f_1 \left( \frac{Q_s}{p} \pm 1 \right) \quad (3)$$

$$f_v = f_1 \left( \frac{Q_r(1-s)}{p} \pm 1 \right) \quad (4)$$

Rotor slots frequency:

$$f_v = \frac{f_1}{p} (1-s)(Q_r \pm p) \quad (5)$$

$$f_v = f_1 \left( \frac{Q_s(1-s)}{p} \pm 1 \right) \quad (6)$$

Frequency generated by dynamic eccentricity:

$$f_v = f_1 \left[ \left( kQ_r \pm n_d \right) \frac{1-s}{p} \pm \nu \right] \quad (7)$$

$$f_d = f_1 \left[ \pm \nu \cdot \frac{1-s}{p} + 1 \right] \quad (8)$$

Frequency generated by static eccentricity:

$$f_v = f_1 \left[ kQ_r \frac{1-s}{p} \pm \nu \right] \quad (9)$$

where:  $Q_r$  or  $Q_s$  - is the number of rotor (stator) slots,  $f_1$  - is the basic harmonic frequency of supply current,  $p$  - is the number of pairs of poles,  $s$  - is the slip,  $k=1,2,3,\dots$ ,  $\nu$  - is the grade of harmonic being sought.

Knowledge of these frequencies helps use the frequency analysis of current flow to perform diagnostics with both the electric asymmetry of rotor as well as other failures, typically the mechanical asymmetry (eccentricity and incorrect alignment). Figure 2 shows typical spectrums of currents for various severity levels of motor failure.

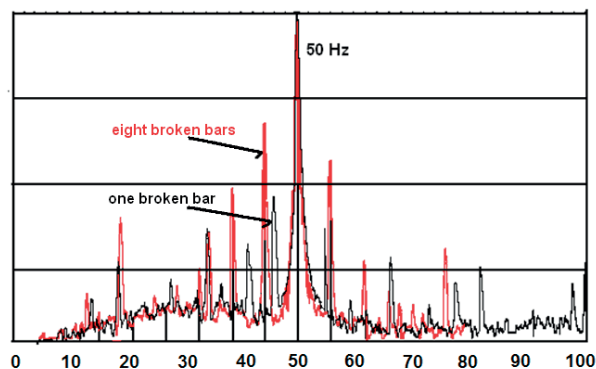


Fig. 2. Standard demonstration of motor failure with various severity levels within the supply current spectrum.

Apart from harmonic analysis, filtration is another method employed to assess a diagnostic value. One of the famous examples is the characteristic proof of asymmetry in motor that becomes evident as an additional frequency appearing in

the machine supply current around the 50% speed level. This frequency is lower, compared to the frequency of basic harmonic; and it can be shown by simple filtering off applied to frequencies above approx. 20%  $f_1$ .

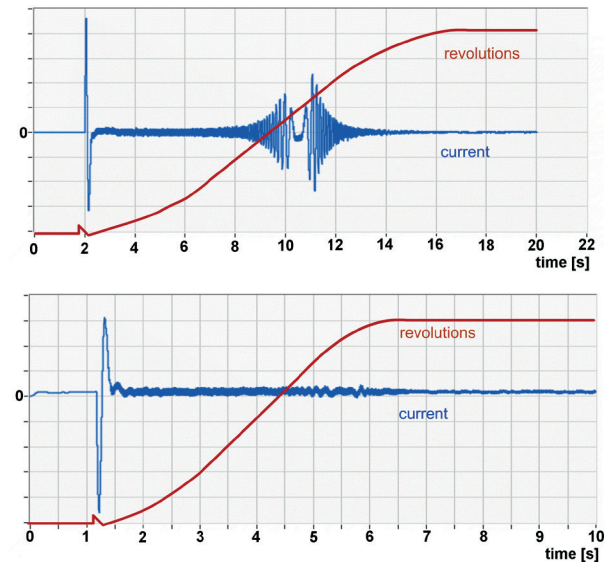


Fig. 3. Filtered record of current during launch on faultless machine and another one with faulty rotor showing a typical demonstration of failure proven by behaviour of the diagnostic value.

Practical application of this method focuses on monitoring of current during motor start-up; this is why it is also called “start-up method”. Its benefit lies in the option to diagnose the starting cage in machine rotor which cannot be diagnosed by any other methods provided within the on-line diagnostic. Figure 3 shows a typical demonstration of motor failure illustrated as a diagnostic value from launch method.

The dominant flow of energy will be accompanied by a whole range of other power effects in case of machine supplied from a frequency converter. If these can be defined, identified or even eliminated, they will not affect the assessment of diagnostic as such, this fact has been proven before [2]. The basic principle of diagnostics conducted on asynchronous machines based on supply current analysis and derived for machinery powered from the mains can be even applied to machinery powered from indirect frequency converters directly and without any substantial alterations or problems. Noise and parasitic frequencies developing due to non-sinusoidal supply can be eliminated efficiently during measurement using analogous or digital filtering and anti-aliasing filters. Any asymmetries will create characteristic frequency lines developed on frequencies that can be determined using the formulas above where the dominant - first harmonic value is the frequency preset at the frequency converter for this machine, so it does not have to be the regular 50Hz. The essential electromagnetic principle of energy transformation remains in the assembly comprising converter-motor-mechanical work, the

stray electromagnetic field then also carries information suitable for diagnostics. The initial worries concerning potential impact of interference on the field measuring chain by occurrence of powerful spurious fields created due to steep initiating processes in the vicinity of such supplied machine and its supply line have not been confirmed. The main portion of switching interference energy is further demonstrated at higher frequency levels only, whereas the diagnostic information is concentrated at the lower end of spectrum close to the dominant harmonic or even between the latter and the zero frequency.

These methods represent a mere fraction of methods already common and developed to a regularly usable level. For the summary of other methods applicable to complex - overall on-line and testing diagnostics of asynchronous machine refer to examples in [2 - 9].

#### 4. Obtaining diagnostic value

The above mentioned diagnostics has been performed using the value allowing to separate the diagnostic information and machine current up until now. Machine current is relatively easy to measure, although there are machines and situations where current as the value measured is hardly available, e.g. on machinery operated in environment with various hazards, e.g. mining areas. Safe performance of diagnostics in this case therefore requires a different value.

Looking at the machine principle and flow of energy throughout its individual components, one would see the role played by electromagnetic field here. It is the field, subject to characteristic distortion by occurring failure that carries such distortion into the supply current as a corresponding image. If we are to obtain the diagnostic value right from the electromagnetic field, the results obtained should match the results achieved by diagnostics based on current. The electromagnetic field is concentrated rather inside the machine and performs the desired work within. However, there is a certain part of electromagnetic field closed outside the frame as a stray field even due to parasitic ways thanks to the design and materials used. Its behaviour over time corresponds with the behaviour of field inside the machine, as well as during the flow of current in machine supply on reciprocal basis.

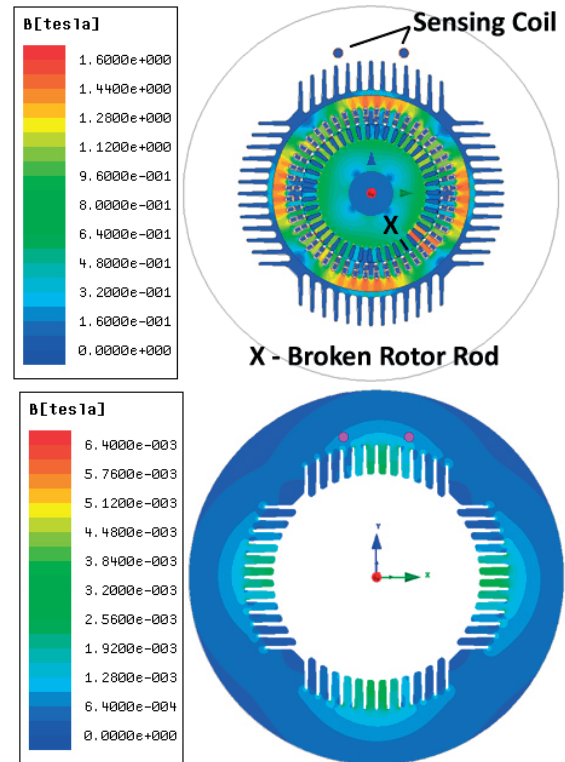


Fig. 4. Distribution of electromagnetic field inside and outside of induction motor with one broken rotor rod at notation X

Figure 4 shows the distribution of electromagnetic field inside and outside - on the surface of asynchronous motor stopped over time - rotation of this field still actually matches rotation of the resultant vector of field inside the machine. Distribution of magnetic flux density is analysed by the help of FEM transient simulation on common design of  $2p=4$  poles induction machine. The simulation also comprises the influence of the one broken rod in rotor on total distribution of magnetic flux density.

Values of electromagnetic induction on the machine frame surface and its close vicinity range within units of mT, this value is still three grades below the value of induction inside machine but it still suffices as the information carrier. Monitoring the behaviour of field changes at one specific surface spot produces a time image corresponding with the current, Fig. 5.

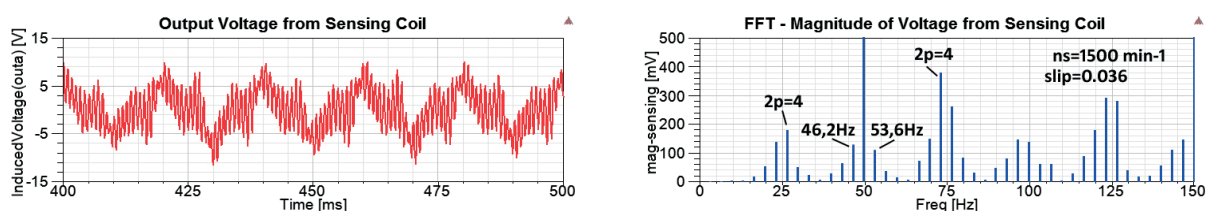


Fig. 5. Time dependence of induced voltage on sensing coil and FFT analysis of this dependence

The stray field of electric machine, as an existing objective value, had been subject to research in the past, most often with respect to electromagnetic compatibility as a matter of fact. Its effects during current induction performed within conductive design elements are also known. Direct measurement of stray field in the machine vicinity as a source of additional information has been utilised in the patent No. DE3722805, for example, providing a description of the method for determination of slip in asynchronous motors used for mining, by measuring of speed with respect to torque characteristic of the particular machine. The rotor current frequency in this method has been determined using the stray magnetic flow outside the motor frame and the frequency signal obtained was then assessed together with the mains voltage of motor subject to measurement. The signal measured was filtered to separate the speed frequency only, corresponding with the mechanical frequency of rotor rotation; this frequency, corresponding to the speed numerically, was the only resultant informative value. Its authors conducted measurement of the magnetic field for non-contact establishment of radial or axial positions of the machine rotor, mostly a synchronous one.

If the stray field and the image of its behaviour over time refer to the field inside machine, the facts above can be followed to perform its diagnostics as its informative value and diagnostic potential are much higher! The bond of machine diagnostic image performed from the stray field using various procedures applicable to diagnostics of behaviour of the supply current with respect to specific machine failures has been clearly proven by contingencies defined above. The contingency between frequency anomalies in the current behaviour with individual typical failures has been proven before by means of many measurements on machines with simulated or actual failures in our laboratory as well as right at industrial sites; that was the reason for repeating these measurements even to prove congruent relations between failures and the behaviour of stray electromagnetic field outside the machine. Monitoring of the diagnostic value was conducted from both the current and field simultaneously with joint assessment producing a clear result – characteristic values of current and field are illustrated by similar means, diagnostics based on the field is therefore not just an accessory, yet rather an equivalent diagnostic method.

The measurement can be conducted using any sensor - decoder for high fidelity conversion of the time path of field changes at a specific spot into another value measurable by regular means (i.e. voltage or current most often). There are two types of sensors applicable in practice; the field probe using Hall Effect or the air-core coil (no regular core coil can be used as the reading could be distorted due to non-linearity and such effect is very hard to predefine). Another benefit of the sensor employed is, besides other, the low internal impedance and parasitic capacity bond, the resultant interference effect caused

by electric fields is therefore low when linked to the measuring chain properly. The number of turns on core has no significant impact on measurement; regular machinery can achieve voltage with amplitude around 1V and usual intensity level of approx. one using a thousand coils. The real absolute value of conversion provided by decoder, i.e. the scale for imaging of certain values in the magnetic field associated with the voltage monitored is not important for diagnostics, most of the frequency (Fourier Fast Transform - FFT) diagnostic methods process the diagnosis using comparative values, usually related to the values measured for some of the dominant harmonic frequencies.

The measuring (sensing) coil is linked to the supply input on upstream gauge or analyser directly. The only substantial aspect is to comply with essential conditions applicable for any diagnostic measurement – the conversion must be independent from frequency within a required scope of monitoring focused on diagnostic value, the measurement process must be also run without over-saturating or overloading of input on the decoder or another gauge used respectively; that also applies to peaks entering the measurement chain through a capacity bond, e.g. due to interference when supplied from a frequency converter.

Application of this method has been verified even in hazardous environment for diagnostics of failures on winding of cutter-loader rotor assembly, it can therefore be considered fit for machinery posing certain trouble or even obstacles when obtaining the diagnostic value with regard to safety matters.

## 5. Conclusion

The method for relatively easy sourcing of diagnostic information from the stray electromagnetic field is under further development and it has been used as basis for a whole range of diagnostic methods focused on diagnostics of particular assemblies within an asynchronous motor. The progress concerns further development of methods and methodology applicable for diagnostics of other failures, especially on stator winding assemblies. Evolving these methods and making them available to experts allow performance of diagnostics of asynchronous motors more efficiently at lower costs, which improve operation economy. Further important benefits arising from the said method include reduction of safety risks associated with diagnostics, which supports extension of its applicability to machinery hard to diagnose due to potential hazards.

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