Slot harmonics in stator current as syptoms of reparation of induction motors

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***Abstract*-Nowadays in many industry branches all over the world more than 90% of all installed motors are of induction motor type. During induction motor operation in electrical parts of stator and rotor circuits (windings) and in mechanical part of the motor and cooperating machine together with coupling elements there occur numerous failures. Every failure brings disturbances in technological process and in worst case leads to whole plant stoppage, what in consequence leads to rise of production costs. In this connection early failure detection on the electrical drives monitoring basis has a great weight. In the paper the attention will be focused on one of the mechanical failures – eccentricity, that is non-axial rotor to stator orientation. There will be presented theoretical considerations and examination results connected with this problem. On the basis of carried out theoretical and experimental considerations there will be made an assessment of stator current signal usability in induction motor operation diagnostics.**

I. INTRODUCTION

The history of failure diagnostics is old as the motor itself. Initially the electrical motors producers and users, to assure safe and reliable operation, have turned to simple protection connected with overcurrents, overvoltages, earth faults, etc.

Nowadays in many industry branches all over the world more than 90% of all installed motors are of induction motor type. During induction motor operation in electrical parts of stator and rotor circuits (windings) and in mechanical part of the motor and cooperating machine together with coupling elements there occur numerous failures. Every failure brings disturbances in technological process, and in worst case leads to whole plant stoppage, what in consequence leads to rise of production costs. In this connection early failure detection on the electrical drives monitoring basis has a great weight.

Therefore to avoid production stoppages, lower the repair costs and lower the operation costs there should be assured ways of their detection and information about their occurrence.

Ideal motor monitoring system should recognize all possible failures kinds which can occur in tested drive. It should be noticed that simultaneous occurrence of several failures gives similar, and even the same, quality effects. Occurrence of such case complicates the estimation of their quantity influence on the machine condition. Without independent standard creation for every failure we cannot estimate the degree in which the particular disturbance affects the total condition of examined circuit.

II. INDUCTION MOTOR FAILURE REVIEW

To assure safe and reliable operation of electrical motors initially the electrical motors producers and users have turned to simple protection connected with overcurrents, overvoltages, earth faults, etc. However electrical motors development, functions performed by them in technological process have feed to diagnostics development. At present non-planned motor standstills can lead to large financial losses.

Main failures of electrical motors can be classified [2]:

1) Stator failures, which lead to break or short-circuit of one or several stator phases,
2) Improper stator winding connection,
3) Rotor rods break or short-circuit ring cracking,
4) Statical or/and dynamical irregularities of air gap,
5) Shaft bend (connected with dynamical eccentricity), which can lead to friction between stator and rotor causing serious damage of stator core and windings,
6) Shorted rotor exciting windings,
7) Transmission and bearing failures.

This failures cause among other things changeable size of the air gap, current asymmetry, pulsating increase of torque, lowering of mean torque, loss increase, efficiency lowering and heat excess.

To detect failures there have been elaborated many diagnostics method. These methods take advantage of achievements form different science [2]:

1) Methods based on stator current spectrum analysis (MCSA – motor current signature analysis),
2) Methods based on measurements of engine noise and vibration,
3) Methods based on flux analysis (additional coils on stator shaft winding),
4) Methods based on artificial intelligence models and neural networks,
5) Methods based on temperature measurement,
6) Methods based on chemical analysis,
7) Radio frequency emissions monitoring,

8) Methods based on infrared radiation recognition.

III. ECCENTRICITY AS FAILURE SOURCE

According to Nandi's [2] motor eccentricity is a state of unequal air-gap which exists between the stator and rotor. Eccentricity detection and diagnosis is a very important element of induction motor condition monitoring. It is caused by very small air-gap toleration between stator and rotor. Small tolerance limit exceed can lead to serious machine failure (stator friction against rotor which in consequence leads to stator or rotor failure), but also deepen the emergency state, caused by other adverse phenomena, such as: asymmetrical feeding, stator or rotor circuit damage, work with excessive load, etc.

Air-gap eccentricity can be a primary or secondary failure. We are speaking about primary failure when the motor has the asymmetry from the operation beginning. It is caused most often by oval stator hole or when the rotor cross-section is not a circle. While when as consequence of sustained non-axial operation the asymmetry of air-gap will exist, then we speak about secondary failure.

We distinguish three types of eccentricity:

- static eccentricity,
- dynamical eccentricity,
- mixed eccentricity (simultaneous occurrence of static and dynamical eccentricity).

In new motors the allowable air-gap eccentricity is up to 10% [2]. Although, the producers try to assure as small as possible total eccentricity level to reduce the vibrations and noise, and to lower the asymmetric radial force.

Most often in motors the mixed eccentricity occurs. In this case the rotation axle can be found between C1 and C2 as shown on figure 1.

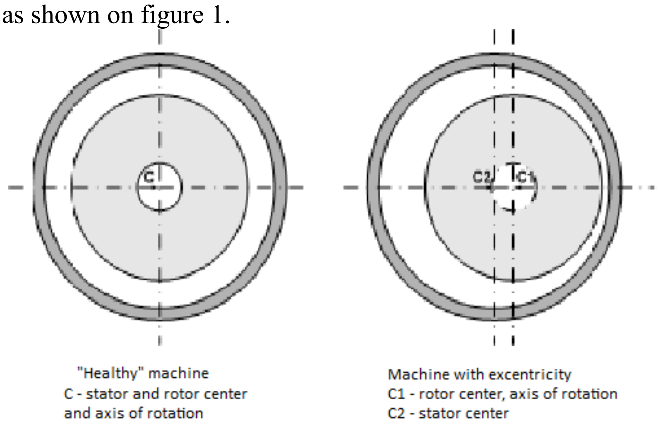

Figure 1. Coaxial and eccentric location of rotor in stator hole

Eccentricity occurrence often does not exclude the motor from further operation. In this case the eccentricity should be detected and controlled because of it's deepen tendency, what in consequence can lead to motor permanent failure.

Eccentricity monitoring and diagnostics causes a lot of trouble because it must be realized during motor normal operating conditions, non-invasive not to change the motor forces. For this reason, except monitoring using X-rays which is very costly, most often applied method is the spectral analysis of stator current.

IV. SLOT HARMONICS IN STATOR CURRENT SPECTRUM

Induction motor rotor out-of–line location in respect to stator brings air-gap asymmetry. Because of characteristic changes of this asymmetry in mutual magnetic couplings between motor windings influences on stator current spectrum form. That is the reason for which the method of stator current spectral analysis (MCSA) is the most often used in eccentricity detection [1].

In case of induction motors characteristic frequencies describing every kind of eccentricity can be written by equation:

$$f_e = f_s\left[\left(kN_r \pm n_d\right)\frac{1-s}{p_b} \pm n_w\right] \tag{4.1}$$

where:

f_s – net frequency, $k = 1,2,3,...$, every integer, N_r – quantity of rotor slots, $n_d = 0$ in case of static eccentricity, $n_d = 1,2,3,...$ in case of dynamical eccentricity (n_d – dynamical eccentricity grade), s – slip, p_b – number of pole pairs, $n_w = \pm 1, \pm 3, \pm 5, \pm 7, ...$ – grade of stator temporal harmonics.

On the ground of dependence (4.1) in stator current there can be determined the frequencies connected with static and dynamical eccentricity and so called principal slot harmonics (PSH). In a healthy motor those harmonics can be used to estimate the angular speed.

Characteristic frequencies connected with static eccentricity are described by the equation:

$$f_{es} = f_s\left[k\frac{N_r}{p_b}\left(1-s\right) \pm 1\right] \tag{4.2}$$

where $k = 0, \pm 1, \pm 2, ...$

In case of simultaneous occurrence of static and dynamical eccentricity harmonics with frequencies positioned near net frequency occurs:

$$f_{ed} = \left| f_s \pm k f_r \right| \quad (4.3)$$

(4.3)

Frequencies described with following dependencies occur in all motors. Low frequencies components cause rising of high frequency components determined by equation (4.1). [1]

5. LABORATORY TESTS

The tests were made using Brüael&Kjaer PULSE 3560 analyzer. For INDUKTA SSh 90L-4 engine with parameters: N_r=26, p_b=2,
and work with nominal load (s=0,0366) we get, basing on equation (4.1), the following harmonics distribution:

Table 1. Theoretical harmonics distribution in stator current spectrum for SSh 90L–4 engine

f_s=50Hz, p_b=2, s=0,0366, n_w=1, k=1, N_r=26			
Component	de, $n_d = -1$	PSH, $n_d = 0$	de, $n_d = 1$
Frequency	652	676	700
de- dynamical eccentricity, PSH- principal slot harmonic			

On figure 2 there are presented chosen examples of stator current spectra for SSh 90L–4 inductive motor.

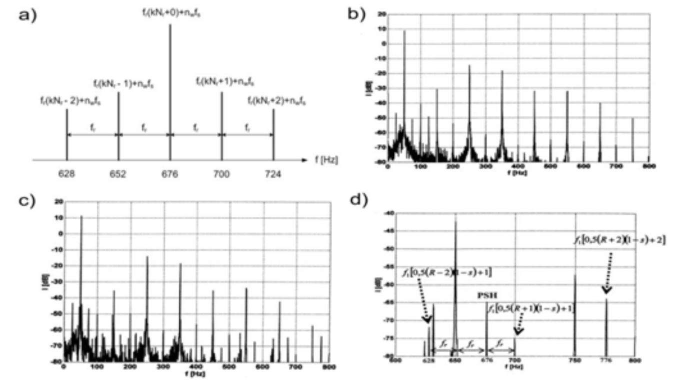

Figure 2. SSh 90L–4 motor stator current spectrum: a) theoretical harmonics distribution in spectrum,
b) motor without load, c) motor with nominal load and out-of-line settlement with machine, d) motor harmonics distribution with nominal load and out-of-line settlement with machine

In table 1 there have been presented calculated frequencies, according (4.1) equation, which may be expected in SSh 90L–4 motor stator current spectrum. The measurements were made on the test stand equipped with Brüael&Kjaer analyzer. The results were presented on 2b–d figures. From comparison of theoretical (2a) and actual (2b, c, d) results we can conclude, that the frequencies characterizing the eccentricity are visible even for an engine with unknown eccentricity (non-damaged motor), what confirms the usability of current spectral analysis in eccentricity diagnostics.

6. FINAL THOUGHTS

Basing on above mentioned considerations and mentioned examples we can formulate the following conclusions:

- Stator current spectral analysis – a great method to monitor, diagnose and valuate of basic failures occurring in inductive motor;
- Detailed analysis is possible with assurance of high resolution of measuring apparatus and wide frequency band in measured signal;
- Spectrum complexity and disturbance presence cause, that diagnosis accuracy largely depends on expert knowledge and experience;
- Diagnosis on the basis of current spectrum depends on harmonics amplitude valuation with characteristic frequencies for given failure;

References

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[2] S. NANDI, "*Condition monitoring and fault diagnosis of electrical motors", IEEE Transactions on Energy Conversion,* Vol. 20, No. 4, December 2005, str. 719-729S