SIMPLE DIAGNOSTIC METHODS FOR DETECTING DAMAGED ROTOR BARS IN SQUIRREL CAGE INDUCTION MOTORS

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Abstract: The paper deals with the damaged rotor cage winding and with the possible methods of detecting the damage. The influence of different levels of damaged rotor bars on the motor run was examined with emphasis placed on experimental measurements. Two detection methods are presented as a low-cost alternative to the more advanced and expensive diagnostic methods. Presented methods are capable of detecting those faults in the rotor bars which have practical impact on the motor run. This makes them especially suitable for quick and everyday use in the services of induction motors.

Key words: damaged rotor bars, fault diagnosis, load characteristics, squirrel cage motor.

1. Introduction

Asynchronous motor is due to its low price and high reliability the most popular electric motor used in many industrial applications. Although they are considered as very reliable in comparison with commutator motors, they can still fail because of some fault. One of the most treacherous faults in squirrel cage motor is the damage of rotor bars (Fig. 1). This fault may not be visible at all and the motor with corrupted rotor can work without any signs of damage for a long time period, unless the fault suddenly becomes serious and eventually disables the motor.

The cause of damaged bars can be various. There can be an inaccuracy in the manufacturing process and the rotor bars can be made in a different shape, cross section or with hidden air bubbles. Rotor bars can be also damaged when the motor is overloaded and overheated for a longer time period and the aluminium in the bars is melted, what can reduce the conductivity of the rotor winding.

Damaged bars in rotor cage winding negatively affect the properties of the motor. Whether the motor will work sufficiently good also with damaged rotor bars depends on the scope of the damage and on the application. In movement sensitive applications even small damage of rotor can cause intolerable deviations from the desired state. However, most of induction motors work in rough applications like water pumps, fans, compressors, etc. These applications are robust enough to withstand negligible change in motor performance characteristics. In this paper the most suitable methods for detecting damaged rotor bars are examined.

Unlike in the machines with wound rotor, in squirrel cage rotor the parameters of cage winding are difficult to measure, since the bars are short circuited one with each other and they cannot be disconnected. There are various techniques developed for detection of broken rotor bars in induction motors. The most popular are vibration measurements [1], temperature measurements [2], measurements which use the coils to monitor the motor axial flux [3] or the radial flux [4]. Popular are also techniques based on monitoring of the stator current spectrum because of its non-intrusive character.

Other methods use the instantaneous power spectrum of one stator phase to calculate a global fault index [5]. The disadvantage of all these methods is that the knowledge of the healthy motor stator current is necessary. One of the techniques which does not require a healthy motor current knowledge is for instance the detection method using the Hilbert transform applied to the line current spectrum modulus obtained by discrete Fourier transform [6].

However, even though these techniques are quite good and sensitive, many of them are unnecessarily difficult and often simply too expensive for detection of broken bars, considering rough applications for which the motors are intended (water pumps, fans, etc.). There was a practical request to develop and test simpler and cheaper diagnostic methods suitable for services of electric machines, which they could use to check the rotors of repaired induction motors. Two methods were developed – the first one, which is based on comparison with reference values of correct rotor and the second one, which does not require any initial information about the examined motor.

2. Damage of rotor bars

Magnetic field created by the rotor cage winding with healthy rotor bars is symmetric. If some of the bars are damaged, the magnetic field created by the rotor is deformed. The level of deformation depends on the type of damage.

To analyze the influence of rotor bar damage on motor properties a squirrel-cage induction motor with the following nominal values was examined: *P=250 W, U = 220 V, I = 1,6 A, n_0 = 1400 rpm.* The stator has a 3-phase winding placed in 24 slots, which can be reconnected to work in a 1-phase mode as well. The rotors used for measurements are shown in Fig. 1.

All of them were damaged by purpose to simulate the fault of rotor cage. The rotors shown in Fig. 1 (a), (b) were damaged by melting out the aluminum from the rotor slots. The rotors in Fig. 1 (c), (d) were damaged by breaking the rotor circuit.
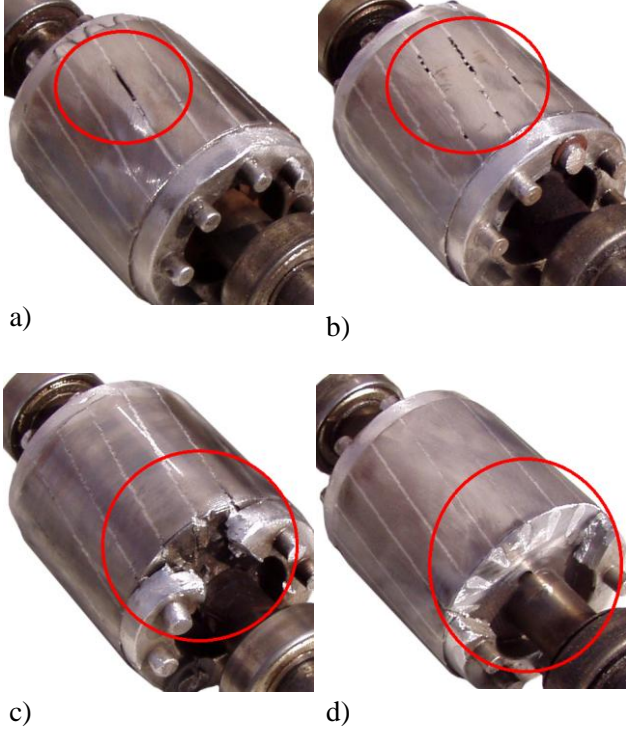

Fig. 1. Examined damaged rotors.
a) 1 damaged bar, b) 3 damaged bars,
c) 2 broken bars, d) 5 broken bars

3. Influence of Damaged Rotor Bars On Motor Performance

To evaluate the quality of proposed diagnostic methods it was necessary to evaluate how much the different damage of rotors influence the performance characteristics of the induction motor.

One new and four different damaged rotors shown in Fig. 1 were placed into the motor and relevant load and heating characteristics were measured.

3.1. Influence of damaged rotor bars on motor load characteristics

In Fig. 2 are shown the measured load torque-speed characteristics of the motor with different rotors. The motor worked in a 3-phase wye connection. It was loaded with torque produced by eddy-current brake and the respective rotational speed of the motor was recorded. From the figure it is obvious that the motors with more damaged rotor are more sensitive to the load torque and they cannot keep up the rotational speed so well.

The measured characteristics correspond to the theoretical assumption, since in case of induction machines with wound rotors there is an obvious relation between the slip, developed torque and rotor winding resistance. The same assumption can be considered also for squirrel-cage induction machines, where the rotor windings consist of bars. The damage of bars can be considered as increase in the rotor winding resistance, although it would be quite difficult to measure the resistance of individual rotor bars exactly and to create the exact mathematical model of the situation.

Theoretical assumption for the slip s in relation with the rotor winding resistance R_2 can be derived from the equation for the torque T_{em} developed by the machine:

$$T_{em} = \frac{m_1 I_2^2 \frac{R_2}{s}}{\omega_m} \tag{1}$$

Where m_1 is the number of stator phases, I_2 is the rotor current referred to the stator and ω_m is the mechanical angular velocity of rotation.

The numerator in (1) is the power transferred across the air gap from the stator to the rotor. The slip is then directly proportional to the rotor resistance:

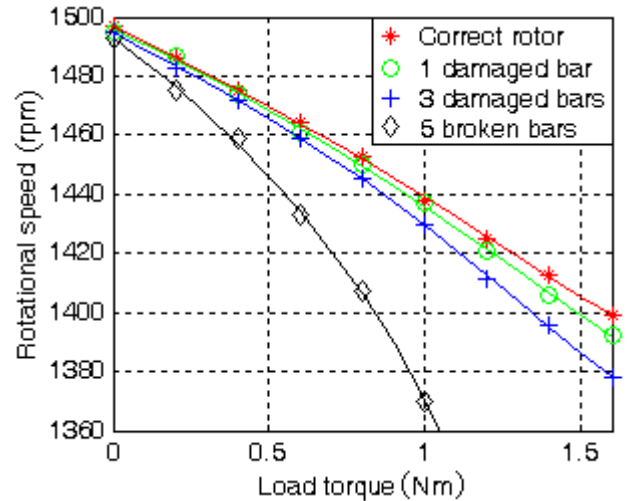$$s = \frac{m_1 I_2^2 R_2}{\omega_m T_{em}} \tag{2}$$

Fig. 2. Load torque-speed characteristics
of 3-phase induction motor with different rotors

The load torque-current characteristics are shown in Fig. 3. Generally, the more the rotor is damaged the higher should be the drawn stator current and the power factor should decrease. However, according to the measurements shown in Fig. 3 the stator current is more easily influenced by the mechanical aspects such as friction than by the light rotor damage. It would be therefore quite difficult to say which rotor is damaged just by evaluating the *RMS*-value of phase current.
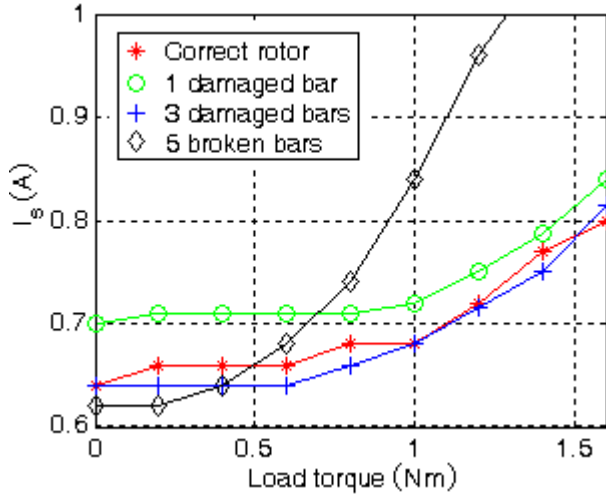
Fig. 3. Load torque-current characteristics of 3-phase induction motor with different rotors

The same measurements as for 3-phase connection were performed also for 1-phase connection of the motor. The characteristics measured for the motor with the most damaged rotor (5 broken bars) are shown in Fig. 4. Surprisingly the 1-phase connection has proved to be more robust and resilient to the speed decrease than 3-phase connection, of course at the cost of lower efficiency. Similar results were obtained for other rotors as well. The 1-phase connection was always better in terms of keeping mechanical speed with damaged rotor, although the stall torque was lower.
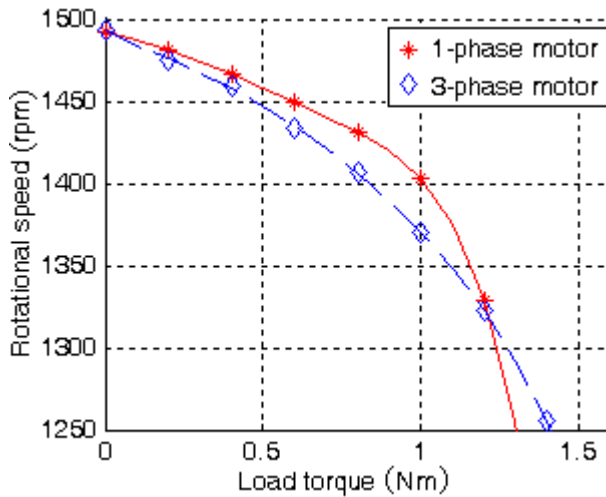

Fig. 4. Comparison of load torque-speed characteristics of 1 and 3 phase induction motor

3.2. Influence of damaged rotor bars on motor temperature characteristics

In order to examine the influence of damaged rotors on the operating temperature of motors the following measurements were carried out. The motors were loaded by the eddy-current brake with torque 0,8 Nm. Fig. 5 and 6 show the rise of temperature measured on the motor surface. The temperatures measured on the winding inside the motor were slightly higher, but with

similar increasing trend. The motor has "B" insulation class, which allows the continual duty with operating temperature up to 130 °C. The measurements were stopped before reaching the allowed temperature, because the motor is designed to drive an industrial fan, which works also as a forced ventilation. However, the fan had to be removed in order to perform the measurements on the motor, what left the motor without any active cooling system.

In Fig. 5 are shown the surface heating characteristics of the motor working in 3-phase connection. The graph shows the temperature rise from the moment when the motors reached the temperature of 35 °C, since there was no visible difference in the curves measured before.

Fig. 6 shows surface temperatures of a motor working in 1-phase connection. The temperatures are generally higher than in case of 3-phase connection, whilst the 1-phase connection works with higher losses than 3-phase connection.
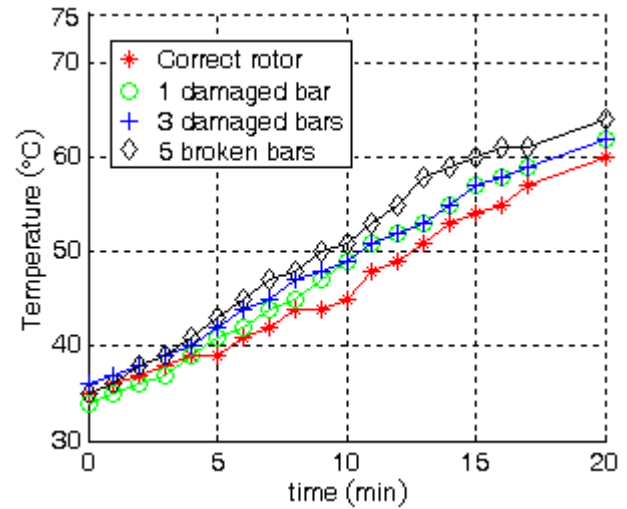

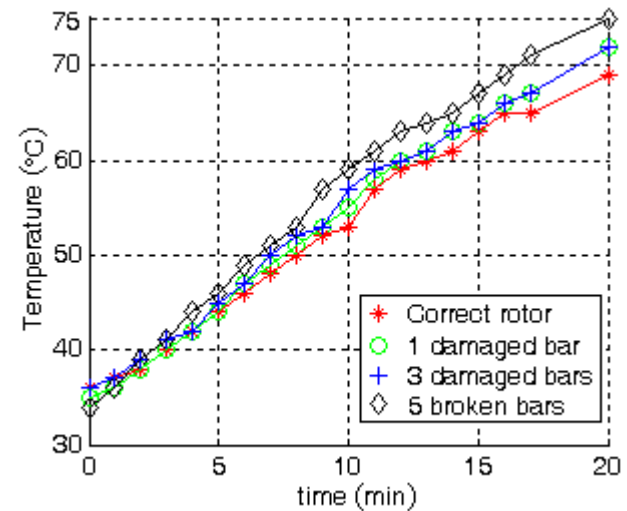Fig. 5. Motor surface heating characteristics in 3-phase connection

Fig. 6. Motor surface heating characteristics in 1-phase connection

The rotor surface temperature profiles shown in Fig. 7 were measured in order to evaluate the influence of damaged bars on the overheating of adjacent rotor bars. The temperature profiles were measured immediately after taking the rotors out from the motor, which was left running in no-load state until the surface temperature reached 85 °C. The temperatures of the rotors were lower than the outer temperature of the stator because the rotor current frequencies in no-load state are low and thus the rotor losses are low, too.
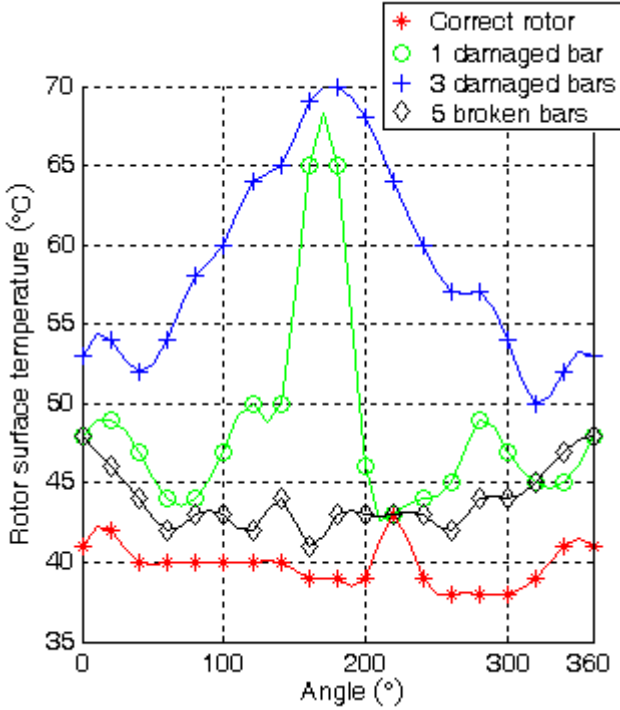

Fig. 7. Rotor surface temperature profiles

The undamaged rotor is generally the coolest one. If one or more rotor bars are damaged (but not broken) the Joule losses in the bars increase. The resulting surface temperature in the vicinity of these bars is therefore higher. The measurements have shown that if one or more bars are broken then the resulting rotor surface temperature in their vicinity is lower. There is very low current flowing in the iron around broken bars and thus there are low power losses in them. In Fig. 7 this is obvious in case of the rotor with 5 broken bars, which has decreased surface temperature around broken bars.

4. Low-Cost Methods for Detecting Damaged Rotor Bars

In this paragraph are presented two low-cost methods suitable for detection of rotor faults. They are precise and sensitive enough to detect the faults of rotor bars which have practical influence on the motor run (evaluated in previous paragraph).

4.1. Method based on the knowledge of healthy motor state

One of the simplest methods how to detect damage of rotor bars is to compare the locked-rotor V-A characteristics. The measurement is quite simple requiring only basic measurement instruments. The locked-rotor V-A characteristics measured for the motor considered in this paper are shown in Fig. 8. With undamaged rotor inside the motor the inductances of stator coils are low. Low impedance of stator phase allows the flowing of higher current. When the rotor winding is damaged, the rotor does not create such strong magnetic field acting against the magnetic field of the stator and therefore the inductance of stator coils increases. Consequently the locked-rotor current is lower depending on how much the rotor winding is damaged. However, it is necessary to have at least one good rotor to measure the reference locked-rotor V-A characteristic. If the locked-rotor current of any other rotor under the same applied stator voltage is different, it can be suspected as damaged. This simple method cannot compete with advanced diagnostic methods in terms of precision, but concerning its simplicity and very low financial costs it can be considered as very practical and useful in many industrial applications.
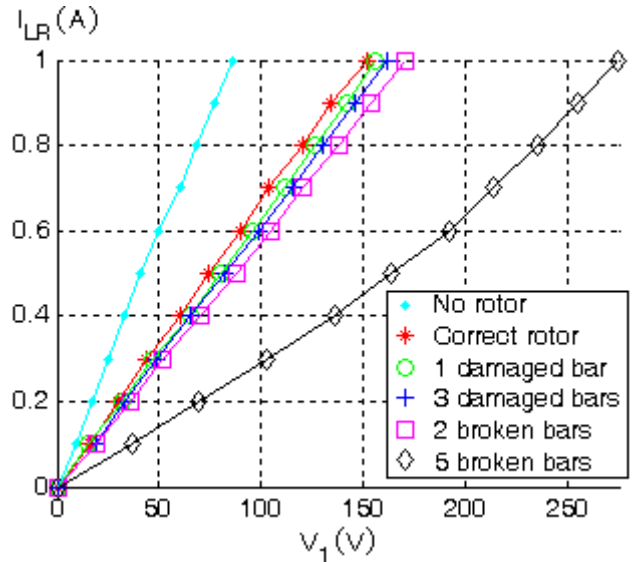

Fig. 8. Locked-rotor V-A characteristics for different levels of rotor bar damage in 3-phase connection

4.2. Method independent on the knowledge of healthy motor state

Another method used for detecting and locating the damage of rotor bars is based on the principle of short circuited turn placed on the ferromagnetic core. When a short circuited turn is placed on the ferromagnetic core of the coil, the magnetic flux created by the current induced in the short circuited turn acts always against the main magnetic flux of the primary coil. In this way it decreases the inductance of the measuring coil. On the contrary, if the short circuited turn is

damaged or broken, i.e. its resistance is increased, there is no such strong magnetic flux acting against the flux from the coil and the inductance of the measuring coil is increased.

The same principle was used for constructing the measurement set illustrated in Fig. 9. The self-inductance of used testing coil was $L_C =147,8\ mH$. When the coil was placed 0,5 mm far from the rotor its self-inductance increased over *175 mH*. It is recommended to measure only one value of inductance per one rotor slot, always in the same relative position.
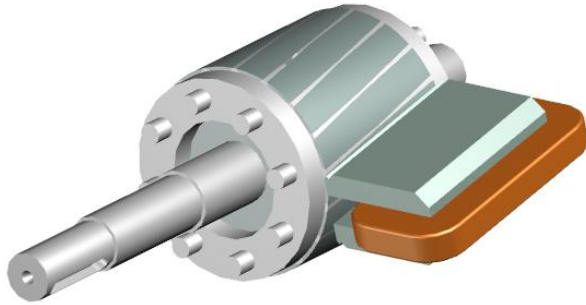

Fig. 9. Illustration of measurement set used for detection of faulty rotor bars
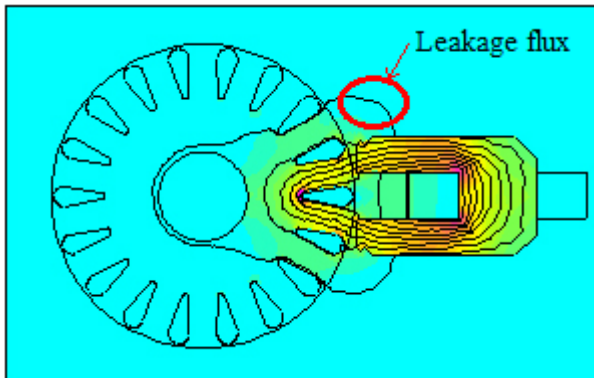

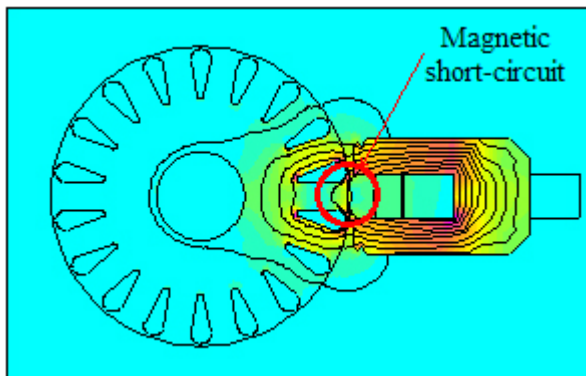Fig. 10. Magnetic field map of measurement set with measuring coil positioned against the teeth

Fig. 11. Magnetic field map of measurement set with measuring coil positioned against the bars

There are two basic positions of the testing coil with regard to the rotor bars in which the measurement can be done.

The respective 2D-FEM analysis of first position is shown in Fig. 10. This is the situation when the coil's ferromagnetic teeth are positioned directly against the rotor teeth. The main magnetic flux is closing through two rotor teeth and through the rotor yoke. After crossing the rotor, the flux lines return through the air-gap back to the iron core of measuring coil. There is also some leakage flux closing through the surrounding air area. Another part of the leakage flux crosses the iron between other rotor bars, which creates other short circuited turns. This affects the precision of the measurement negatively, but even with this shape of measuring coil the results are sufficient enough. This is the basic position recommended for measurement, when the inductance of the testing coil should be recorded.

Another possible basic position is illustrated in Fig. 11, where the coil teeth are facing the rotor bars. This position is not very useful for measuring inductance, since a big part of the magnetic flux is short-circuited through the middle rotor tooth. Due to high leakage flux the influence of rotor winding on the primary coil is lowered and the measurement is distorted. The measured inductance of testing coil is in this case generally higher and it is more difficult to locate the damaged rotor bars.

By using this measurement set it was possible to evaluate the health of the rotor bars without knowing the reference values of healthy rotor. Some preliminary measurements were already published in [8], however the shape of coil used there was not optimized yet and the coil was not skewed. The dependence of coil inductance on rotor rotation angle (displacement) is shown in Fig. 12. When the rotor bars are undamaged, they create a sort of short circuited turn on the secondary side of the transformer and the inductance of primary coil is low. When they are damaged, or even completely broken, their magnetic flux cannot act against the main magnetic flux so strongly and the inductance of primary coil is increased. It is quite simple to allocate the damaged rotor bars during the measurement. However, the allocation may not be so clear, especially when there are only very small defects in the rotor bars. But according to the measurements presented in paragraph 3 of this paper, smaller defects in the rotor cage winding would have only negligible influence on the performance of simple industrial motors for which the measurement method is proposed.
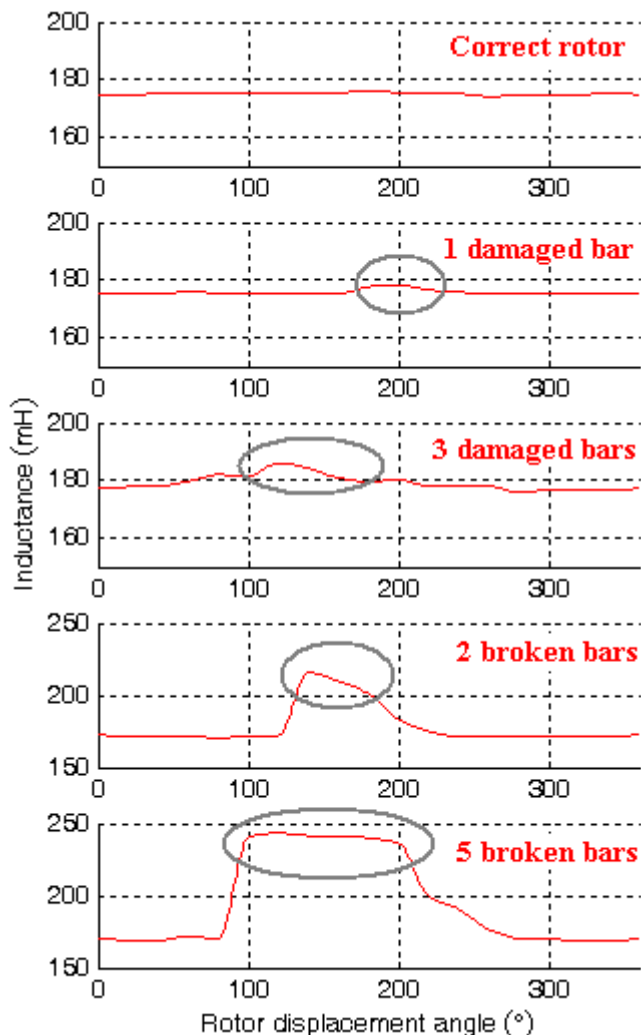
Fig. 12. Measured inductances of testing coil for various rotors

5. Conclusion

There are many advanced methods how to detect damaged bars in the rotor, however many of them are based on difficult analyses, require skilled staff and expensive devices.

There was a practical request to develop and test simpler, yet reliable diagnostic methods suitable for services of electric motors. Most of repaired induction motors are from simple and robust applications, which can withstand smaller damages in the rotor cage. The method needed to be sensitive enough to detect at least those defects, which have practical impact on motor performance.

Methods proposed in this paper use simple measurements of locked-rotor V-A characteristics or inductance. They cannot compete with advanced laboratory methods in terms of precision. However, testing measurements confirmed the reliability of presented methods in detecting non-negligible rotor faults.

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