In this paper, a case study is presented which demonstrates the efficiency of vibration analysis in induction motor rotor fault detection and diagnosis. Vibration signals of a 3.15 MW induction motor were acquired. The observed motor is specific due to its very low slip, which can cause some difficulties in fault diagnostic process. Employing some of well-known signal processing and analysis techniques, characteristic features in frequency domain were observed. Using the previous experience in fault detection and diagnosis, it is determined that a rotor fault, a broken bar in specific, is present in the motor. Based on this analysis, a general repair of the motor was carried out and the diagnosed fault was confirmed. This way, applying the fault detection and diagnosis in early fault stage, some serious malfunctions and failures were avoided, which resulted in decreased repair costs and undisturbed delivery of heat energy during the heating season.

Key words: Fault diagnosis, induction motor, vibration analysis.

INTRODUCTION

Induction motors are the primary movers of the industries because of their rugged configuration, low cost, versatility, reasonably small size and capability to operate with an easily available power supply. In the practical applications, however, they are subjected to the unavoidable stresses, such as electrical, environmental, mechanical and thermal stresses, which create failures in different motor parts (Bonnet and Soukup, 1988). These failures disturb the safe operation of induction motors, threaten the normal manufacturing and, accordingly, result in the substantial cost penalties.

The issue of robustness and reliability is very important to guarantee the good operational condition of the entire industrial system. Therefore, condition monitoring of induction motors has received considerable attention in recent years. Early fault diagnosis and condition monitoring can reduce the consequential damage, breakdown maintenance and reduce the spare parts of inventories. Moreover it can prolong the machine life and increase the performance and the availability of machine.

The condition of an induction motor is mostly examined from the signals acquired through the sensors and supporting instrumentation methods. Signals can manifest fault signature using an appropriate signal processing technique. A number of induction motor condition monitoring techniques have been developed, which monitor a certain parameter of the motor and determine its health. These techniques are based on monitoring various variables, such as acoustic emission, air-gap torque, electromagnetic field, instantaneous power, vibration, voltage, stator current and other (Benbourid, 2000; Finley et al, 2000; Matić et al, 2010; Matić et al, 2012; Mehrjou et al, 2011).

Rotor is the most inner part of the induction motor, which is rotated by an electromagnetic field induced in its coils from the stator field. The rotational force is then applied to the external equipment. Induction motor rotors are very rugged, but still, rotor defects such as broken bar, cracked end-ring, bent shaft and eccentricity do occur. These failures do not initially cause motor to fail, but they bring about secondary effects that lead to a serious malfunction, so detection of these faults plays an important role.

This paper deals with detection of broken rotor bar using vibration signal analysis, which is one the oldest condition monitoring techniques, characterized by easy measurability, high accuracy and reliability. A case study is presented, where a faulty 3.15 MW induction motor was examined and the presence of broken rotor bar was detected. The paper is organized as follows: in section 2 some basics of broken rotor bar detection using vibration analysis are presented, in section 3 the observed system, data acquisition equipment and the results obtained using signal processing techniques are described, and section 4 concludes the paper.

MATERIAL AND METHOD

The rotor bars can be partially or completely cracked during the operation of induction motor, due to stresses, improper rotor geometry design or some imperfection in material or rotor production process. The bar breakage is the major fault in the rotor of induction motor. Once a bar breaks, the condition of the
neighboring bars also deteriorates progressively due to the increased stresses. To prevent such a cumulative destructive process, the problem should be detected early, that is, when the bars are beginning to crack.

Vibration signal analysis is a fault detection technique which is generally used for mechanical faults diagnosis, such as bearing problems, gear mesh defects, rotor misalignment and mass unbalance (Kanović et al., 2011; Singh and Al Kazzaz, 2003). However, it can also be successfully applied to detect broken rotor bar, since this fault excites the electromagnetic field disturbance and thus intensifies the torque modulations and vibrations of the motor, which can be measured by placing vibration sensors on motor housing (Climente-Alarcon et al., 2012; Kanović et al., 2012; Neale et al., 1979; Tavner and Penman, 1987).

Analyzing the obtained vibration signals in frequency domain, using for example Fast Fourier Transformation (FFT), one can note some fault-specific features in signal spectrum, which imply the presence of the particular fault.

If a broken rotor bar exists, no current will flow in that bar. As a result, the field in the rotor around that particular bar will not exist. Therefore the force applied to that side of the rotor would be different from that on the other side of the rotor, creating an unbalanced magnetic force that rotates at one times rotational speed and modulates at a frequency equal to slip frequency times the number of poles, which is known as pole pass frequency. It means that in vibration spectrum increased amplitudes will occur at the rotation frequency $f_r$ and its sidebands $f_{rbp} = f_r \pm f_p$

where $f_p$ is pole pass frequency defined as

$$f_p = \left( f_{sync} - f_r \right) \cdot P$$

with $P$ being number of poles and $f_{sync}$ being synchronous speed (Finley et al., 2000). These sidebands occur also in higher harmonics of rotation speed ($2f_r, 3f_r, ...$). Detection of broken bar based on vibration analysis and observation of features (1) and (2) is common in literature and widely used in practical applications (Mehrjou et al., 2011).

One must note that pole pass frequency defined in (2) is highly slip-dependent. The low value of slip causes the rotation frequency $f_r$ to be close to synchronous speed $f_{sync}$, and sidebands to be closer to the central frequency, which makes them less distinctive in vibration signal spectrum. This fact can cause difficulties if the motor operates under low load, and consequently with low slip, since in that case fault detection reliability is questionable. Therefore, vibration signals must be acquired when motor operates close to full load in order to have sidebands that can be clearly distinguished from central frequencies. This is the main flaw and limitation when features (1) and (2) are used for fault detection, since the applicability and reliability of the results depends on motor load, meaning that low slip is undesirable.

If we still need to examine an induction motor operating under low load, some additional features can be considered. Namely, broken rotor bar will also result in increased vibration amplitude at rotor bar pass frequency $RBPF$

$$RBPF = f_r \cdot Nr$$

and its sidebands modulated at two times the frequency of the power source $f$

$$f_{rbp} = RBPF \pm 2f$$

In (3), $Nr$ is number of rotor bars (Singh and Kazzaz, 2003). This characteristic feature is not slip-dependent and, combined with previously mentioned features, it can provide more reliable fault detection results in case of low load condition. However, since number of rotor bars varies from 16 to 60 or more, the value of $RBPF$ can be very high, implying the examination of high frequency domain of vibration spectrum. This demands high sampling rates for signal acquisition which is the reason why $RBPF$ is a parameter not frequently used in fault detection due to hardware-imposed limitations. Still, when motor operates with very low slip and the reliability of low frequency features (1) and (2) is questionable, the observation of vibration amplitudes at RBPF and its sidebands can confirm broken bar diagnosis and augment the overall reliability of the results (Neale et al., 1979; Singh and Kazzaz, 2003).

The subject of the present research was to detect fault(s) on a 3.15 MW high-voltage induction motor with fabricated rotor consisting of 56 bar, driving a low- and high-pressure pump in a heating plant, depicted in Fig. 1.

Fig. 1. A 3.15 MW high-voltage induction motor driving low- and high-pressure pumps in heating plant, which was the subject of fault detection.

The faulty operation of this particular motor was manifested through high level of vibration and acoustic noise and decreased momentum when operating under load, which implied the presence of broken bar. However, the costs of motor disassembling and rotor removal were considerably high, especially having in mind that periodic maintenance was not in schedule, so it was necessary to determine the nature of the fault and to recommend the procedure for its elimination.

RESULTS AND DISCUSSION

Vibration signals were collected through two shear accelerometers, attached by magnetic mount, as shown in Fig. 2.

Fig. 2. Two shear accelerometers with magnetic mounting used for radial and axial vibration signal collection.
Radial and axial vibration signals were recorded, containing 100,000 samples collected with 10 kHz sampling rate. The signals were acquired from faulty motor and from the other motor which was assumed to be healthy, being the same type as the faulty one and driving the same type of pumps. The research was conducted in the summer period, when the plant was not in operation. The signals were collected at two different operation point, one with lower load, and the other with higher load level, approximately 40% and 60% of nominal load, respectively. The nominal load could not be achieved, since the heating plant was not in operation. The slip value, measured using stroboscope, was 0.0010 (0.10%) for the first operation point and 0.0016 (0.16%) for the second operation point. The rotation frequencies were calculated to be 49.95 Hz and 49.9 Hz for the first and second operation point, respectively. The number of poles $P$ equals two and the power source frequency $f$ is 50 Hz, which is also equal to synchronous motor speed $f_{sync}$. Using these data, characteristic features defined by (1) - (4) can be calculated.

The time-domain signals were processed using FFT and signal spectra were obtained for both healthy and faulty motor, depicted in Fig. 3 - 5.

![Fig. 3. Vibration spectra of faulty and healthy motor – low frequency domain, lower load level (slip 0.10%)](image)

In Fig. 3, showing low frequency domain vibration spectra of both healthy and faulty motor at the first operation point, one can only note the increased vibration level of faulty motor at rotation frequency. Since the load level is low, sidebands $f_{brb1}$ are not distinguished. The increased vibration amplitude at the rotation frequency of the faulty motor is notable also in Fig. 4, depicting low frequency domain vibration spectra at the second operation point. Although the slip value is still very low, rotation frequency sidebands $f_{brb1}$ for faulty motor are distinctive, implying the presence of broken bar.

Since in both operating points the slip was very low, in order to increase diagnosis reliability, high-frequency domain features were also considered. Observing Fig. 5, one can note the increased vibration amplitude of faulty motor at rotor bar pass frequency $RBPF$ and its sidebands $f_{brb2}$, which confirmed the fault diagnosis and led to the conclusion that at least one rotor bar is broken.

![Fig. 4. Vibration spectra of faulty and healthy motor – low frequency domain, higher load level (slip 0.16%)](image)

![Fig. 5. Vibration spectra of faulty and healthy motor – high frequency domain, higher load level](image)

Based on the presented results of fault detection, the suggestion was to disassemble the motor and to remove the rotor in order to be examined in detail, despite high costs of this operation. As shown in Fig. 6, after rotor removal it was determined that two rotor bars were completely broken at their endpoints, which confirmed the results of fault detection procedure.

![Fig.6. The rotor after disassembling; two broken rotor bars at the end rings can be observed](image)

**CONCLUSION**

This paper presents a case-study where vibration signal analysis was applied to detect presence of broken rotor bar in high power induction motor. The vibration signals were collected and processed and some characteristic spectral features
were observed. Since the motor operates with very low slip, beside some well-known and widely used low-frequency features, some additional features in high-frequency domain were also considered. Based on the results of fault detection procedure, it was suggested to remove the rotor and inspect its condition, which confirmed the fault diagnosis, proving that vibration analysis can be successfully applied in detection of induction motor rotor faults.

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