Analysis of Squirrel Cage Motor with Broken Bars and Rings

MIKSIEWICZ Roman

Silesian University of Technology, Gliwice, Poland

Abstract — **In the paper results of calculations and measurements of an induction motor with broken bars or rings are presented. The calculations were made using the circuit and circuit-field method. The stator current as diagnostic signal for estimation of a damaged squirrel cage motor has been taken. For separation of additional components in the stator current arising at a rotor asymmetry low-pass filters of Mathcad program were used.**

Keywords — *Electric machine, induction motor, broken bars, diagnostic.*

I. INTRODUCTION

Diagnostic of electric motors, especially large motors, is currently important operations issue from point of view of electric drives reliability. Therefore in last years it is observed great interest of this subject matter. Many publications where diagnostic signals subject for analysis have arisen (diagnostic signals: available waveforms of stator currents, machine vibrations, etc.) on the basis of such analysis estimation of the damaged squirrel cage is made. It is proposed to use band filters, FFT analysis, wavelet analysis, artificial neural network, Kalman filters and other [1, 2, 3, 4, 6, 7, 8]. However, no one of above methods gives information concerning number of broken bars and their distribution. No one method gives information if a damage concerns bars or squirrel cage rings. In the stator current no additional components arise in case of symmetric damages, therefore such waveform may not be used as a diagnostic signal. In practice it is possible by periodical carrying out measurements to deduce about arising damages by comparison of current waveforms.

This study is aimed at examination of the influence of the rotor bars and rings damages on time waveforms of the stator currents and comparison of the circuit and circuit-field methods with results of tests carried out on a real motor. As diagnostic signal for analysis of the current waveforms were used band-pass filters from Mathcad program. In the stator current spectrum when the rotor is damaged the components with frequency f_p dependent on slip appear

$$f_p = \left(1 \pm 2\,k\,s\right) f_s \qquad (1)$$

Also quasi-static mechanical characteristics of a motor for damaged rotor bars and rings were compared.

The squirrel cage motor built on the basis of a wound rotor has been used as the analysis object. In this motor the stator winding has not been changed while the rotor has been made as the cage with special construction allowing making breaks in any bar or in rings from one side of the rotor.

The basic data of the motor are the following: $P_N = 4$ kW, supply voltage $U_N = 380$ V, power supply frequency $f_N = 50$ Hz, rotational speed $n_N = 1470$ rpm, stator slot number $Q_S = 36$, rotor slot number $Q_r = 24$, star connection, two-layer winding.

II. CIRCUIT MODELING OF THE MOTOR

A. Mathematical model

In order to make analysis of time current waveforms during motor start-up while asymmetry in rotor exists the machine model in phase coordinates [5] has been formed. For simplification it were assumed linear magnetic circuit of a 3-phase symmetric induction machine, uniform air gap, sinusoidal distribution of the winding (mono-harmonic model), constant values of motor parameters. The rotor squirrel cage winding with Q_r slots is represented by Q_r of phase windings corresponding to Q_r closed loops of the cage formed by linked bars and connecting them fragments of rings sections (Fig. 1).
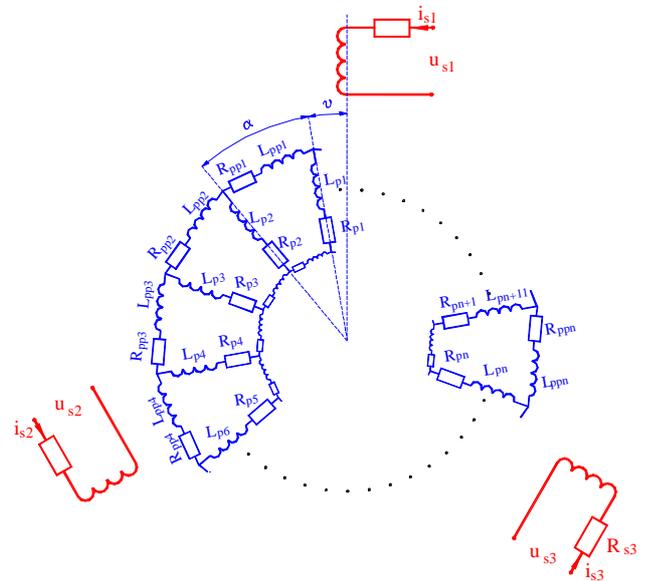

Fig.1. Electrical circuits of the squirrel cage motor

The model characterized in the above way is described in phase coordinates:

♦ *system of three voltage-current equations of the stator*

$$[u_s] = [R_s][i_s] + [L_{\sigma s}]\frac{d}{dt}[i_s] + [M_{ss}]\frac{d}{dt}[i_s] + \frac{d}{dt}([M_{sr}(\vartheta)][i_r]),\tag{2}$$

♦ *system of Q_r voltage-current equations of the rotor (where current coordinates of the rotor are closed loop currents in the cage)*

$$[0] = [R_r][i_r] + [L_{\sigma r}]\frac{d}{dt}[i_r] + [M_{rr}]\frac{d}{dt}[i_r] + \frac{d}{dt}([M_{rs}(\vartheta)][i_s]),\tag{3}$$

♦ *equation of mechanical state*

$$J\frac{d\Omega_m}{dt} = T_e - T_m,\tag{4}$$

where

$$T_e = [i_s]^T \frac{\partial}{\partial\vartheta}[M_{sr}(\vartheta)][i_r],\tag{5}$$

$$\vartheta = \int_0^t \Omega_m dt + \vartheta(0)\tag{6}$$

$[R_s]$ - matrix of stator phase winding resistances,

$[L_{\sigma s}]$ - matrix of stator phase winding leakage inductances,

$[M_{ss}]$ - matrix of stator-stator mutual inductances,

$[M_{sr}(\vartheta)]$ - matrix of stator-rotor mutual inductances,

$[R_r]$ - matrix of rotor winding resistances,

$[L_{\sigma r}]$ - matrix of rotor bars and rings leakage inductances,

$[M_{rs}(\vartheta)]$ - matrix of rotor-stator mutual inductances ($[M_{rs}(\vartheta)] = [M_{sr}(\vartheta)]^T$),

T_e - electromagnetic torque of the motor,

J - moment of inertia,

T_m - mechanical load torque on machine shaft,

ϑ - rotor rotation angle,

$\vartheta(0)$ - initial rotor rotation angle between the axis of stator first phase and the axis of rotor cage first closed loop at t = 0 (Fig. 1).

The system of differential equations (2)÷(4) is non-linear system composed of (Q_r + 4) equations with variable coefficients [5]. Nonlinearity of equations (2) and (3) results from non-linear relation of elements of the inductance matrix $[M_{sr}(v)]$ and $[M_{rs}(v)]$ and the rotor rotation angle v, that is a non-linear function of time. Nonlinearity of equation (4) is related to expression for electromagnetic torque (5).

In the presented mathematical model various cases of damages in the rotor (breaks of cage, breaks of rings) may be modeled by setting a suitably large resistance for the given bar or ring.

B. Results of calculations of the circuit model of motor

For the above mentioned motor it were made calculations for damaged successive rotor bars and rings. Calculations were performed for start-up of the motor with an increased moment of inertia, assuming negative initial rotational speed.

Exemplary results of calculations of the torque and stator currents are presented in Figure 2.

Both broken bars and rings cause arising of additional pulsations in the torque and additional components in the stator phase currents (1) that may be in practice used as a diagnostic signal.
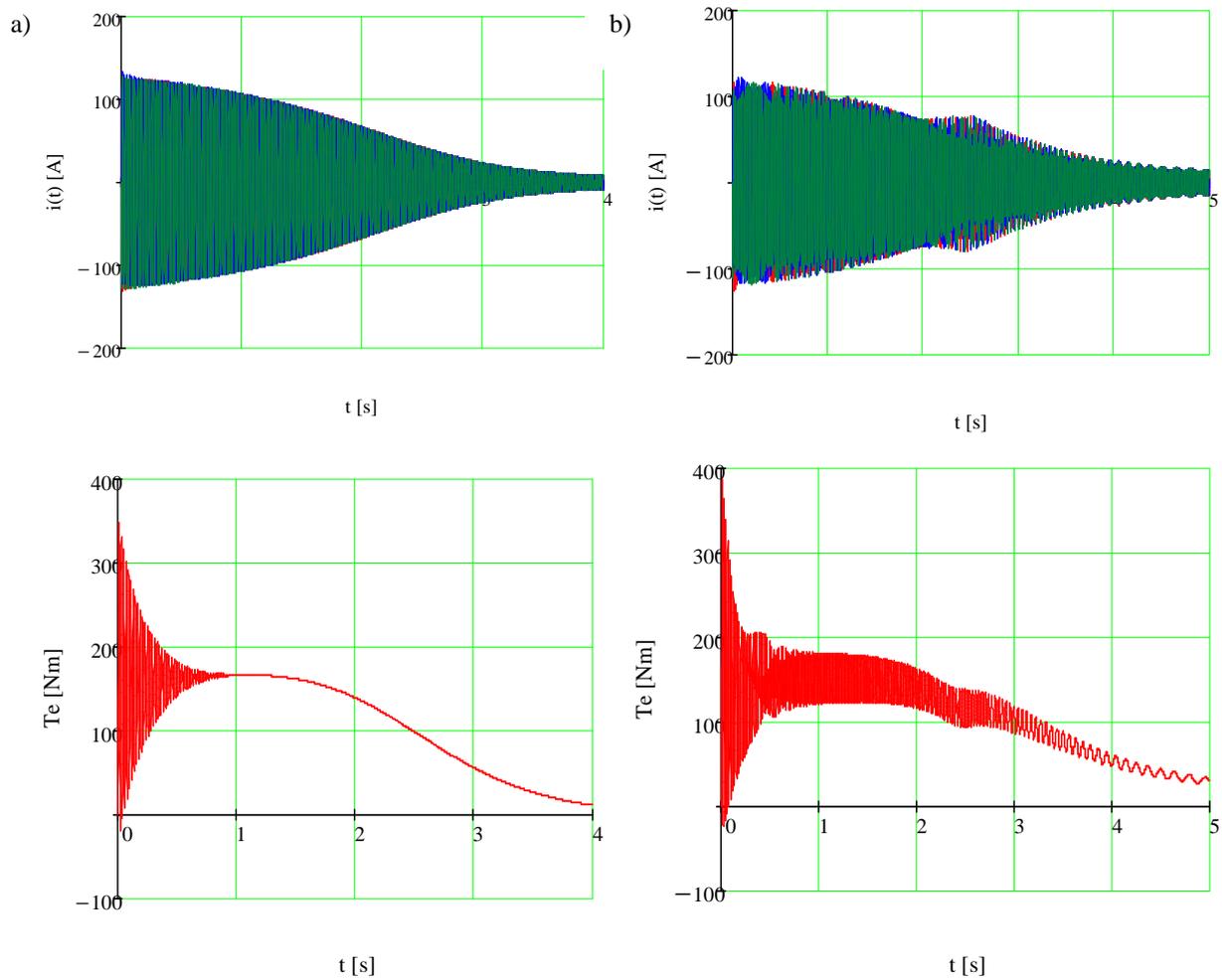
Fig.2. Waveforms of the stator currents and torques for healthy rotor (a) and for 4 broken bars, during motor start-up
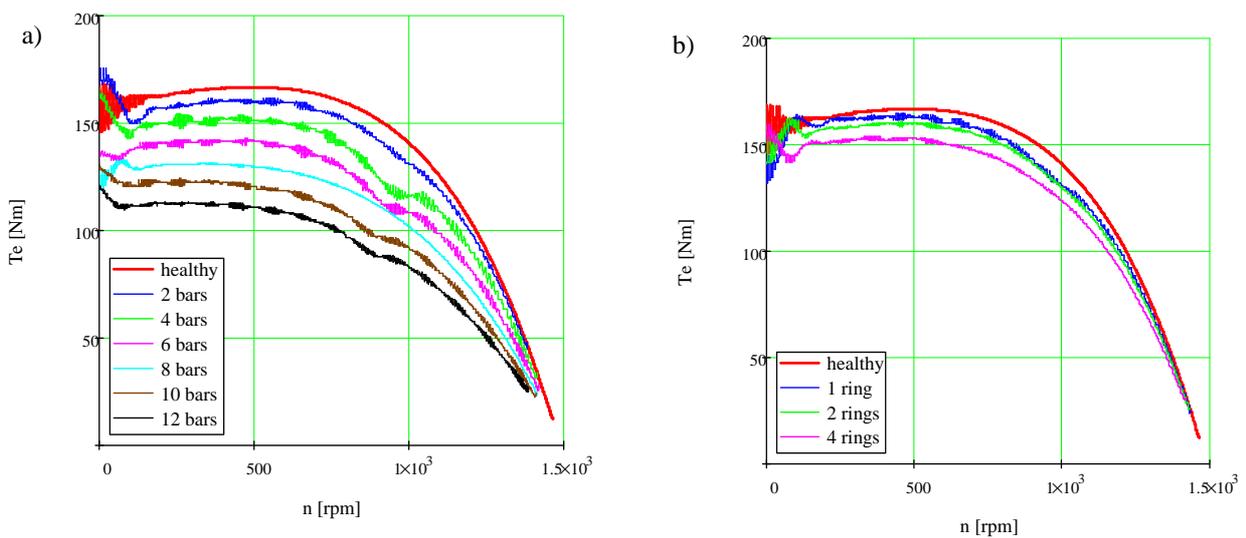

Fig.3. Characteristics of average torque vs rotor speed for broken bars (a) and broken rings (b)

As have been mentioned above the stator current may be used as the diagnostic signal of rotor damages. For this purpose it were used procedures of filtration available in Mathcad program. In Figure 3 there are presented filtered out current waveforms as a function of rotational speed for various types of damages using a low-pass filter.
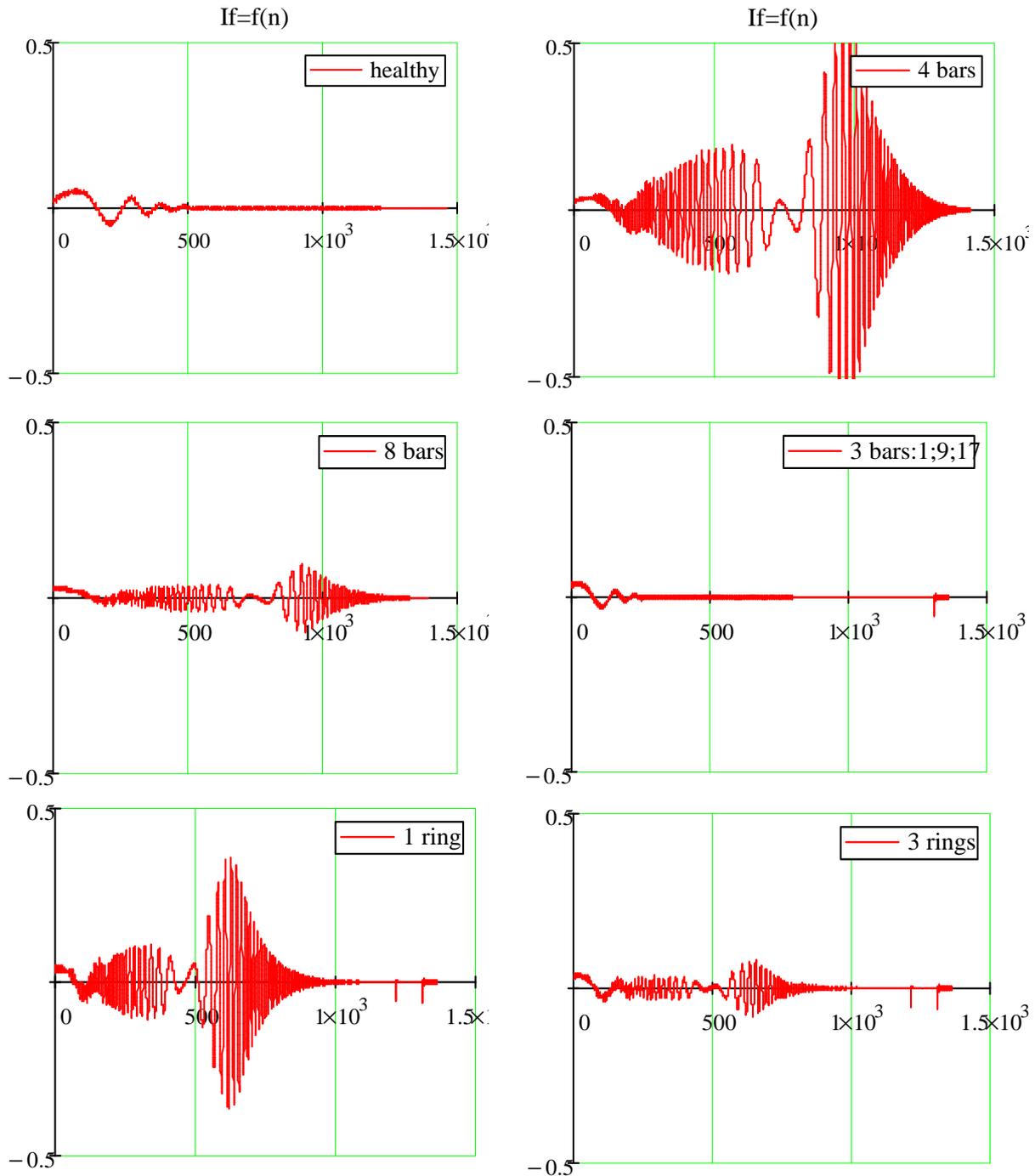
Fig.4. Filtered waveforms of the stator currents vs rotational speed for different number of broken bars or broken rings

III. FIELD-CIRCUIT MODELLING OF THE MOTOR

For the analyzed motor it were performed also circuit-field calculations using FEM (Fig. 5). In calculations it were not taken into consideration motor iron losses. For the two-dimensional model the leakage inductances of stator winding ends and rotor rings were included into the circuit diagram of the Maxwell program.
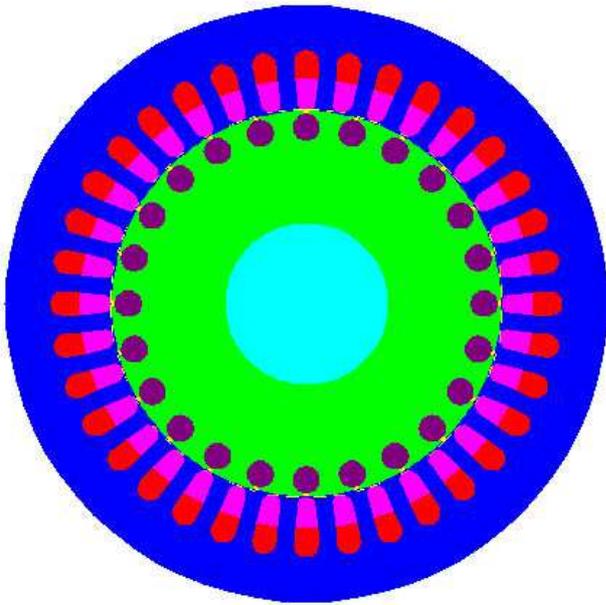
Fig.5. Field model of the rotor

In Figure 6 waveforms of torque during start-up of not damaged squirrel cage and the motor with 4 broken bars are presented. The tested motor generates large synchronous torques that beyond the synchronous speed become pulsating torques with large amplitudes. Therefore, comparing results of the circuit-field calculations (Fig. 6) and results of the circuit calculations for the mono-harmonic model (Fig. 2) it is possible to notice the essential difference in the waveforms of these torques.

The effect of broken cage bars is an increase of the current in adjacent bars. In Figure 7 time waveforms of currents in 6 bars of cage, in bars adjacent to 2 broken bars are presented.

When waveforms of stator currents subjected to treatment described previously the filtered out waveforms were obtained (Fig. 8) for various cases of bars and rings breaks.
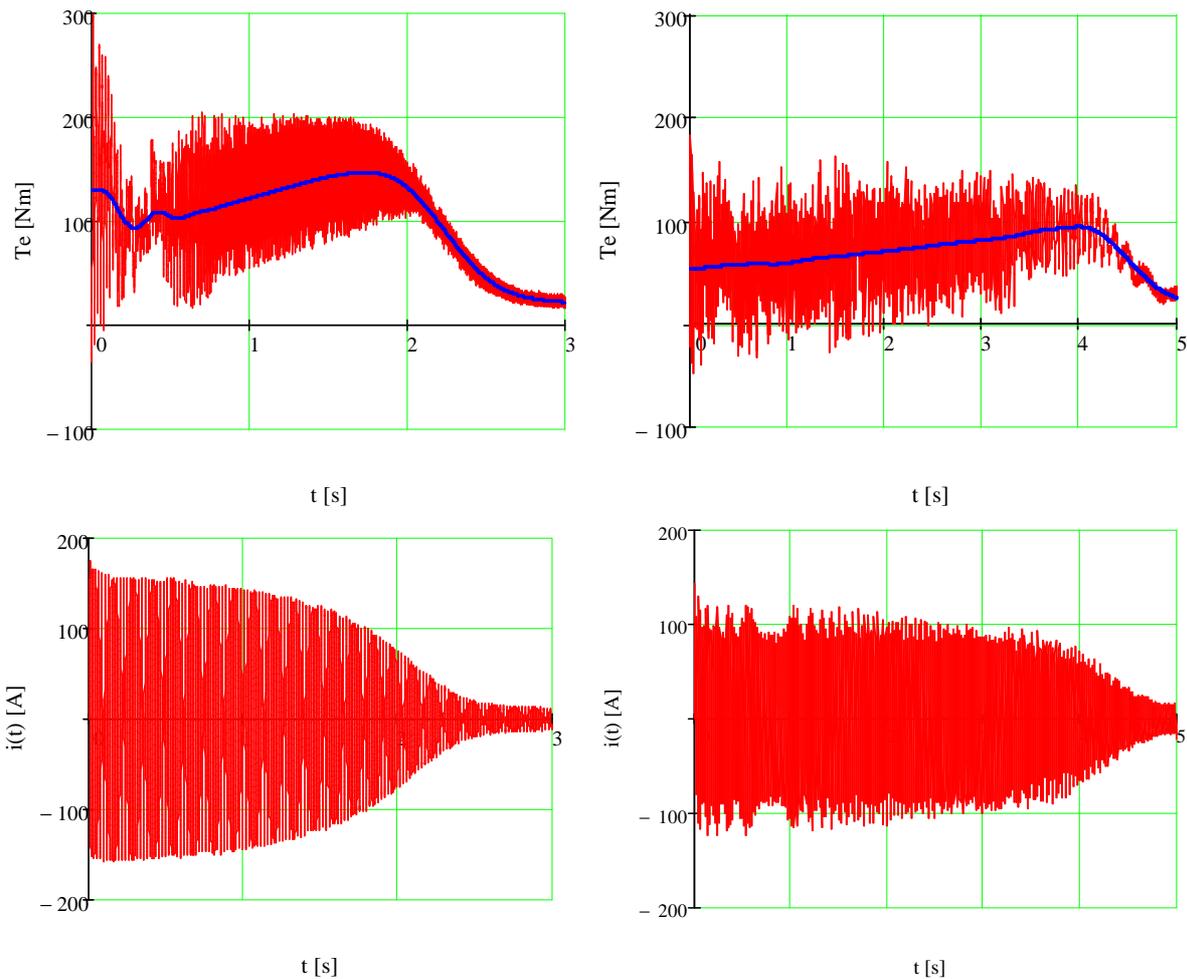

Fig.6. Waveforms of the stator currents and torques for healthy rotor (a) and for 4 broken bars
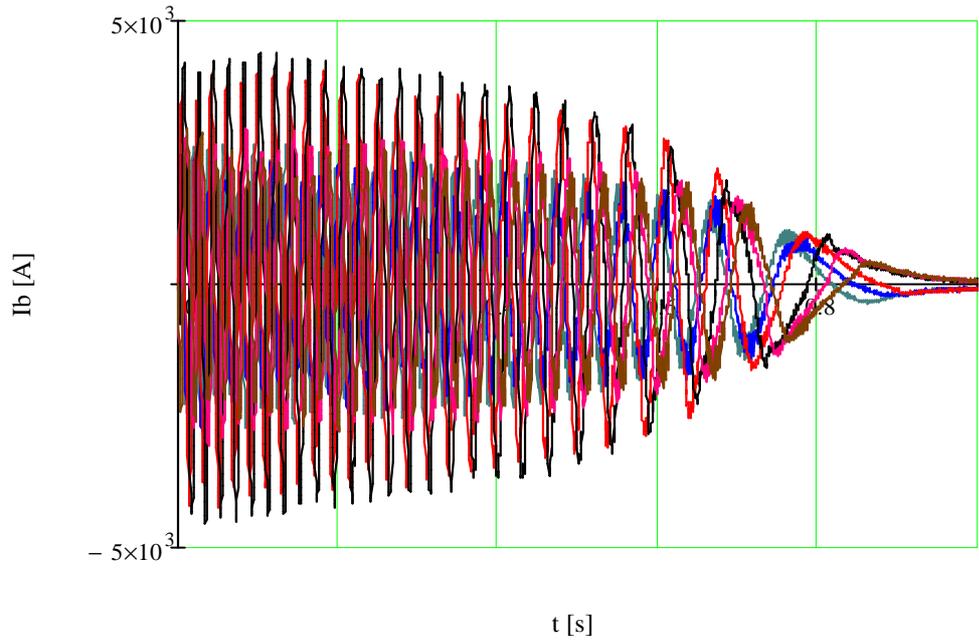
Fig.7. Waveforms of currents in the bars adjacent to 2 broken bars, during motor start-up
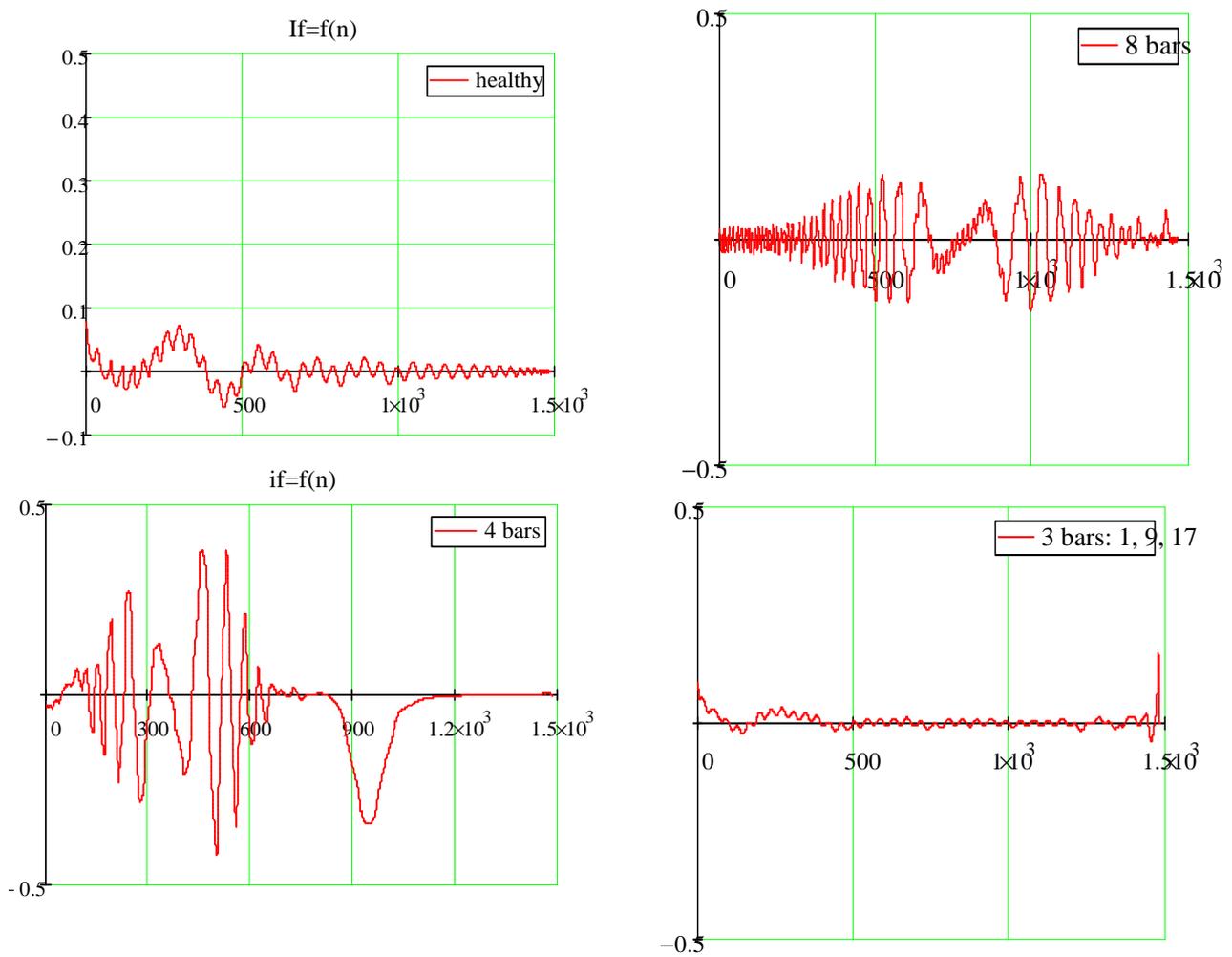

Fig.8. Filtered waveforms of the stator currents vs rotor speed for different number of broken bars or broken rings

IV. MEASUREMENTS RESULTS

In the analyzed motor it was possible to disconnect any number of cage bars. Currents measurements were made for various types of the rotor damage during motor start-up at an increased moment of inertia. Filters of the same type as in case of currents from derived calculations were used for the current analysis. In Figure 9 some of current waveforms are presented.
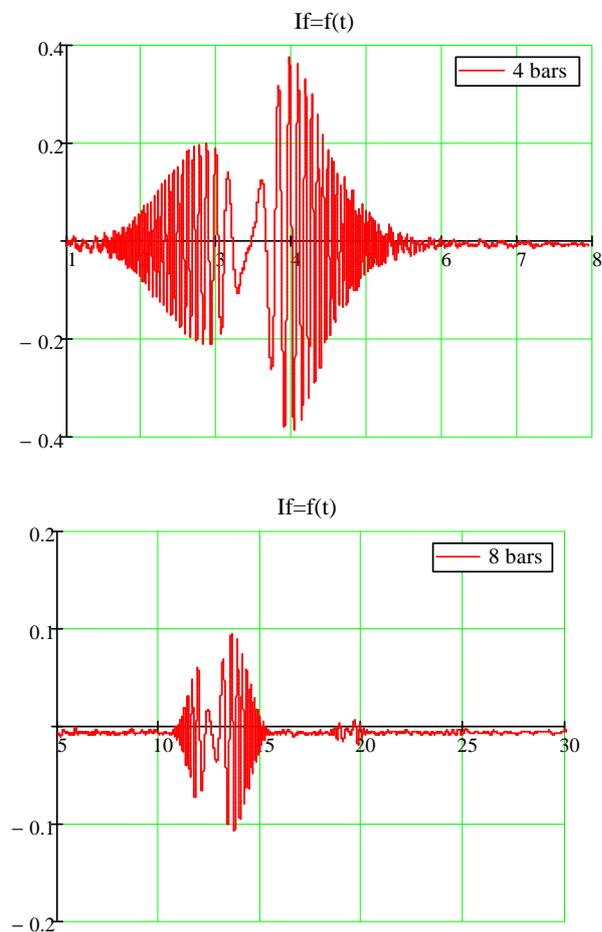

Fig.9. Filtered waveforms of the stator currents for different number broken bars or broken rings, during motor start-up

V. CONCLUSIONS

• While analyzing filtered current waveforms during motor start-up is possible to get notice accordance the results from measurements and both circuit and circuit-field obtained calculations.

• Damages of rotor bars and rings lead to change of electric-mechanical characteristics of the motor; in a lower degree for the damaged short-circuiting ring, in a greater degree for broken bars.

• When the number of broken bars is not great the torque at stopped motor may be even greater.

• Increase of the broken bars number results in an increase of the alternate component in the electromechanical torque.

• The broken bar in the rotor cage results in an increase of currents in adjacent bars – in practice it causes an temperature increase in these bars, increase of mechanical stresses and other breaks.

• Application of digital band filters allows after separation of additional component of the stator current to use it as diagnostic signal. But this signal does not comprise information concerning number of the damaged bars or rings.

• The principle saying that increase of damaged bars results in an increase of additional component of the stator current is in general not true. In case of the analyzed motor when 8 bars were damaged this component was lower than in case of 4 damaged bars.

• Depending on the rotor bars number it may arise cases of symmetric distribution of breaks, in such a case no additional components in current arise. In this motor such component does not arise when symmetric breaks of 3 bars arise.

• In practice, when diagnostic method of the stator current filtration during motor start-up is used, it is necessary to make such measurements periodically and by comparison of them to examine if change of an additional stator current occurs.

VI. REFERENCES

[1] Da Silva A.M, Povinelli R.J., Demerdash N.A.: *Induction Machine Broken Bar and Stator Short-Circuit Fault Diagnostics Based on Three-Phase Stator Current Envelopes*. IEEE Transactions On Industrial Electronics, Vol. 55, No. 3, March 2008, pp.1310-1318.

[2] Dybowski P.: *Diagnostyka silnika indukcyjnego z zastosowaniem sygnału skutecznej wartości ruchomej prądu*. Zeszyty Problemowe - Maszyny Elektryczne, 2007, Nr 77, str.27-32.

[3] Faiz J., Ebrahimi B.-M.: *A New Pattern for Detecting Broken Rotor Bars in Induction Motors during start-up*. IEEE Transactions On Magnetics, Vol. 44, No. 12, December 2008, pp.4673-4683.

[4] Janik T., Różycki A.: *Urządzenie diagnostyczne do wykrywania asymetrii elektrycznej klatek silników indukcyjnych*. Przegląd Elektrotechniczny. 1988, z.4, str.106-108.

[5] Kluszczyński K., Miksiewicz R.: *Modelowanie 3-fazowych maszyn indukcyjnych przy uwzględnieniu wyższych harmonicznych przestrzennych przepływu*. Zeszyty Naukowe Politechniki Śląskiej. Elektryka z.142. Gliwice 1995.

[6] Kowalski Cz., Kanior W.: *Ocena skuteczności analiz FFT, STFT i falkowej w wykrywaniu uszkodzeń wirnika silnika indukcyjnego*. Prace Naukowe Instytutu Maszyn, Napędów i Pomiarów Elektrycznych Politechniki Wrocławskiej, 2007, Nr 60.

[7] Sanchez M.P., Guasp M.R., Daviu J.A.A., Folch J.R., Cruz J.P., Panadero R.P.: *Instantaneous Frequency of the Left Sideband Harmonic During the Start-Up Transient: A New Method for Diagnosis of Broken Bars*. IEEE Transactions On Industrial Electronics, Vol. 56, No. 11, November 2009, pp. 4557-4570.

[8] Xie Y.: *Characteristic Performance Analysis of Squirrel Cage Induction Motor With Broken Bars*. IEEE Transactions On Magnetics, Vol. 45, No. 2, February 2009, 759-766.