ROTOR FAULTS OF THE INDUCTION MOTORS

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Abstract

This contribution describes model of the induction motor with rotor faults. From the simulation are obtained stator and rotor currents, speed and torque. From these data is predicted time behaviour of the induction motor with broken ring or bar (one or more).

1 Introduction

In electric motor is converted electromagnetic energy into mechanical energy. This conversion is made in the air gap of motor between rotor and stator.

Model of the induction motor is composed from 3 equations – stator voltage equation (1), rotor voltage equation (2) and mechanical equation (3) .

$$\mathbf{U}_s = \mathbf{R}_{ss}\mathbf{I}_s + \frac{d\mathbf{\Phi}_s}{dt} \tag{1}$$

$$0 = \mathbf{R}_{rr}\mathbf{I}_r + \frac{d\mathbf{\Phi}_r}{dt} \tag{2}$$

$$\frac{d\omega_r}{dt} = \frac{p}{J}(T_e - T_L)\,;\quad \frac{d\Theta_r}{dt} = \omega_r\,;\ T_e = I_s \frac{dL_{sr}}{d\Theta_r} I_r \tag{3}$$

These equations relate to healthy and faulty induction cage motor. Rotor faults have got influence on the resistivity $\mathbf{R}_{RR}$, rotor inductance $\mathbf{L}_{RR}$ and mutual inductances $\mathbf{L}_{RS}$ or $\mathbf{L}_{SR}$. These matrixes depend on the rotation of the rotor (angular rotor position) as well.

2 Stator equations

Equation (1) is stator model. Stator resistance $\mathbf{R}_{ss}$ is constant diagonal matrix (4) where R_S is resistance of i-th stator coil.

$$\mathbf{R}_{ss} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \tag{4}$$

$$R_s = R_{as} = R_{bs} = R_{cs} \tag{5}$$

Stator flux $\mathbf{\Phi}_{ss}$ compounds from self stator flux and mutual stator-rotor flux (6).

$$\mathbf{\Phi}_{ss} = \mathbf{L}_{ss}\mathbf{I}_s + \mathbf{L}_{sr}\mathbf{I}_r \tag{6}$$

Self stator inductance $\mathbf{L}_{ss}$ is a constant matrix (7). In the next is considered symmetric stator matrix (7) with parameters (8).

$$\mathbf{L}_{ss} = \begin{bmatrix} L_{s1} & L_{s1s2} & L_{S1S3} \\ L_{s2s1} & L_{s2} & L_{s2s3} \\ L_{s3s1} & L_{s3s2} & L_{s3} \end{bmatrix} \tag{7}$$

$$L_{ss} = L_{s1} + L_{ms} = L_{s2} + L_{ms} = L_{s3} + L_{ms} \tag{8}$$

$$L_{sisj} = -\frac{L_{ms}}{2},\ L_{ms} = \frac{\mu_0 \cdot l \cdot r \cdot N_s^2 \cdot \pi}{4 \cdot g}$$

Mutual stator-rotor inductance $\mathbf{L}_{sr}$ (9) isn´t constant matrix. This matrix is the function of the actual angular position between rotor bars and stator coils. Dependence is in equation (8). L_{sirj} is inductance between i-th stator phase and j-th rotor loop.

$$\mathbf{L}_{sr} = \begin{bmatrix} L_{ar1} & \cdots & L_{ar(Nr)} \\ L_{br1} & \cdots & L_{br(Nr)} \\ L_{cr1} & \cdots & L_{cr(Nr)} \end{bmatrix} \tag{9}$$

$$L_{sirj} = L_m\ (\Theta_r + \frac{(2i-1)}{2}\alpha_r - (j-1)\frac{2\pi}{3}) \tag{10}$$

where

$$L_m = L_{ms}\frac{4\sin(\frac{\alpha_r}{2})}{N_S \pi};\ \alpha_r = \frac{2\pi}{N_r}$$

3 Rotor equations

Rotor model is based on the equivalent circuit of rotor cage electrical connection fig. 1. In this circuit are all rotor bars replaced by rotor bar resistances and inductances. Rotor end rings are divided into N_r parts (segment). All parts consist segment of end ring resistance and segment of end ring inductance.

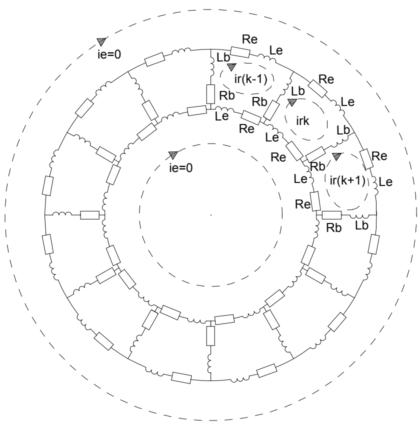

Figure 1 – Equivalent circuit of rotor cage electrical connection

Rotor is formed by $(N_r + 1)$ loops. The k-th loop equation is below(11). End ring loops are in equation (12). We assume that I_e is equal zero. And the equation (12) is neglected.

$$U_{rrk} = 0 = 2(R_b + R_e)I_{rk} - R_b I_{r(k-1)} - R_b I_{r(k+1)} - R_e I_e + \frac{d\Phi_{rrk}}{dt} \tag{11}$$

$$U_{re} = 0 = -R_e I_{r1} - R_e I_{r2} - \ldots - R_e I_{rNr} + nR_e I_e + \frac{d\Phi_{rr}}{dt} \tag{12}$$

In the rotor voltage equation (2) is $\mathbf{R}_{rr}$ the rotor resistance matrix (13). This matrix is derived from system of rotor loop equations (11).

$$\mathbf{R}_{rr} = \begin{bmatrix} R_0 & -R_b & 0 & \ldots & -R_b & -R_e \\ -R_b & R_0 & -R_b & \ldots & 0 & -R_e \\ \vdots & \ddots & \ddots & \ddots & \vdots & \vdots \\ -R_b & 0 & 0 & \ldots & R_0 & -R_e \\ -R_e & -R_e & -R_e & \ldots & -R_e & N_r R_e \end{bmatrix} \tag{13}$$

where R_b, R_e – the rotor bar and end ring resistance,

$R_0 = 2(R_e + R_b)$ – the auxiliary variable.

$$\mathbf{\Phi}_{rr} = \mathbf{L}_{rr}\mathbf{I}_r + \mathbf{L}_{rs}\mathbf{I}_s \tag{14}$$

Rotor flux is compound from self rotor flux and mutual rotor- stator flux (14). Self stator inductance $\mathbf{L}_{rr}$ is a constant matrix (15).

$$\mathbf{L}_{rr} = \begin{bmatrix} L_{kk} + L_0 & L_{ki} - L_b & L_{ki} & \ldots & L_{ki} - L_b & -L_e \\ L_{ki} - L_b & L_{kk} + L_0 & L_{ki} - L_b & \ldots & L_{ki} & -L_e \\ \vdots & \ddots & \ddots & \ddots & \vdots & \vdots \\ L_{ki} - L_b & L_{ki} & L_{ki} & \ldots & L_{kk} + L_0 & -L_e \\ -L_e & -L_e & -L_e & \ldots & -L_e & N_r L_e \end{bmatrix} \tag{15}$$

where $R_0 = 2(L_e + L_b)$ – auxiliary variable,

L_{ki}, L_{kk} – mutual inductances between rotor bars.

$$L_{ki} = -\frac{\mu_0 lr}{g}\alpha_r^2, k \neq i \quad , \ L_{kk} = \frac{\mu_0 lr}{g}\alpha_r\left(1 - \frac{\alpha_r}{2\pi}\right)$$

Mutual rotor and stator inductances are equal to (16), these are variable matrixes. These matrixes depend on actual angular position between rotor bars and stator coils.

$$\mathbf{L}_{rs} = \left[\mathbf{L}_{rs}\right]^T = \begin{bmatrix} L_{a1} & L_{b1} & L_{c1} \\ L_{a2} & L_{b2} & L_{c2} \\ \vdots & \vdots & \vdots \\ L_{aN_r} & L_{bN_r} & L_{cN_r} \end{bmatrix}^T \tag{16}$$

$$L_{ai} = L_m \cdot \cos\left(\Theta_r + (i-1)\alpha_r + \frac{\alpha_r}{2}\right) = \frac{L_m}{2}\left(e^{+j\left(\Theta_r + (i-1)\alpha_r + \frac{\alpha_r}{2}\right)} + e^{-j\left(\Theta_r + (i-1)\alpha_r + \frac{\alpha_r}{2}\right)}\right) \tag{17}$$

$$L_{bi} = L_m \cdot \cos\left(\Theta_r + (i-1)\alpha_r + \frac{\alpha_r}{2} - \frac{2\pi}{3}\right) = \frac{L_m}{2}\left(e^{+j\left(\Theta_r+(i-1)\alpha_r+\frac{\alpha_r}{2}-\frac{2\pi}{3}\right)} + e^{-j\left(\Theta_r+(i-1)\alpha_r+\frac{\alpha_r}{2}-\frac{2\pi}{3}\right)}\right) \tag{18}$$

$$L_{ci} = L_m \cdot \cos\left(\Theta_r + (i-1)\alpha_r + \frac{\alpha_r}{2} + \frac{2\pi}{3}\right) = \frac{L_m}{2}\left(e^{+j\left(\Theta_r+(i-1)\alpha_r+\frac{\alpha_r}{2}+\frac{2\pi}{3}\right)} + e^{-j\left(\Theta_r+(i-1)\alpha_r+\frac{\alpha_r}{2}+\frac{2\pi}{3}\right)}\right) \tag{19}$$

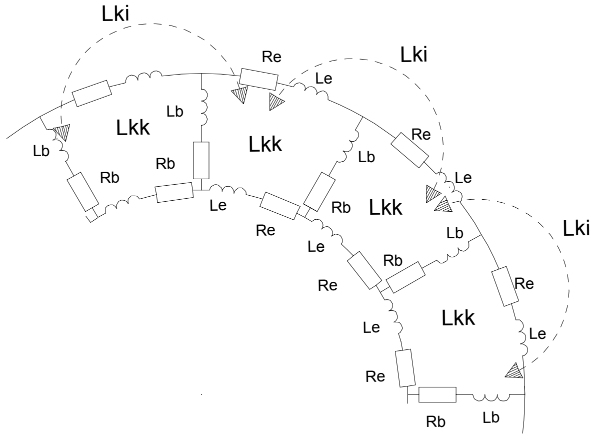

Figure 2 – Inductances in the equivalent circuit of rotor cage electrical connection

4 Torque equation

The torque is in the equation (20). In this equation is covered energy transfer from stator through air gap into rotor (real power).

$$\frac{d\omega_R}{dt} = \frac{p}{J}(T_e - T_L)\ ;\quad \frac{d\Theta_R}{dt} = \omega_R\ ;\quad T_e = I_s \frac{dL_{SR}}{d\Theta_r} I_r \tag{20}$$

5 Induction motor model after a space vector transformation

The three phase to two axis transformation is below. Stator currents and rotor currents can be replaced by vectors I_{rdq} and I_{sdq} (21) and (22) .

$$I_{sdq} = K_s \cdot \begin{bmatrix} 1 & \alpha & \alpha^2 \end{bmatrix} \cdot \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} = K_s\left(I_{as} + e^{j\frac{2\pi}{3}} \cdot I_{bs} + e^{-j\frac{2\pi}{3}} \cdot I_{cs}\right) \tag{21}$$

$$I_{sdq} = K_s \frac{3}{2} I_{sm} e^{j\omega t} = I_{sd} + j \cdot I_{sq} \tag{22}$$

$$I_{rdq} = K_r \begin{bmatrix} 1 & \beta^1 & \cdots & \beta^{Nr-1} \end{bmatrix} \begin{bmatrix} I_{r1} \\ I_{r2} \\ \vdots \\ I_{rNr} \end{bmatrix} = K\left(I_{r1} + e^{j\frac{2\pi}{N_r}} \cdot I_{r2} \ldots e^{j\frac{2\pi}{N_r}(N_r-1)} \cdot I_{rN_r}\right) \tag{23}$$

$$I_{rdq} = K_r \frac{N_r}{2} I_{rm} e^{j\omega t} = I_{rd} + j \cdot I_{rq} \tag{24}$$

$$\alpha = e^{j\frac{2\pi}{3}} ; \beta = e^{j\frac{2\pi}{N_r}} \tag{25}$$

In equations (21) to (24) are K_s and K_r constants. When we investigate current, constants are $K_s = 2/3$, $K_r = 2/N_r$. The transformations to the reference coordinate system rotating at angular speed ω_k are in (26) and (27).

$$I_{sdq}^k = K_{sk} I_{sdq} e^{-j\omega_k t} \tag{26}$$

$$I_{rdq}^k = K_{rk} I_{rdq} e^{-j(\omega_r t - \omega_k t)} \tag{27}$$

Induction motor model in the stator reference frame is described by equations (28) to (30) and the same model in the common rotating reference frame is described by equations (31) to (33).

$$U_{dqs} = R_s I_{dqs} + \left(L_{1s} + \frac{3}{2} \cdot L_{ms} \right) \frac{d}{dt} I_{dqs} + \frac{3}{2} \frac{K_s}{K_r} \cdot L_m \cdot \frac{d}{dt} \left(e^{+j(\Theta_r + \delta)} \cdot I_{dqr} \right) \tag{28}$$

$$0 = 2\left[R_e + R_b (1 - \cos\alpha_r)\right] I_{dqr} + \frac{d}{dt} \left\{ \begin{array}{l} \frac{N_r}{2} \frac{K_r}{K_s} \cdot L_m \cdot e^{-j(\Theta_r + \delta)} \cdot I_{dqs} + \\ + \left[\frac{\mu_0 \cdot l \cdot r \cdot \alpha_r}{g} + 2 \cdot L_e + 2 \cdot L_b \cdot (1 - \cos\alpha_r) \right] \cdot I_{dqr} \end{array} \right\} \tag{29}$$

$$T_{em} = \frac{L_m}{2} \cdot \frac{1}{K_s \cdot K_r} \operatorname{Im}\left(e^{+j\left(\Theta_r + \frac{\alpha_r}{2}\right)} \cdot I_{dqs}^* \cdot I_{dqr} - e^{-j\left(\Theta_r + \frac{\alpha_r}{2}\right)} \cdot I_{dqs} \cdot I_{dqr}^* \right) \tag{30}$$

$$\left(L_{1s} + \frac{3}{2} \cdot L_{ms} \right) \cdot \frac{d}{dt} I_{dqs}^k + \frac{3}{2} \cdot \frac{K_s}{K_r} \cdot \frac{K_{sk}}{K_{rk}} L_m \cdot \frac{d}{dt} I_{dqr}^k = U_{dqs}^k - \left[\begin{array}{l} R_s \cdot I_{dqs}^k + \left(L_{1s} + \frac{3}{2} \cdot L_{ms} \right) \cdot \omega_k \cdot j \cdot I_{dqs}^k + \\ + \frac{3}{2} \cdot \frac{K_s}{K_r} \cdot \frac{K_{sk}}{K_{rk}} L_m \cdot \omega_k \cdot j \cdot I_{dqr}^k \end{array} \right] \tag{31}$$

$$\frac{N_r}{2} \frac{K_r}{K_s} \cdot \frac{K_{rk}}{K_{sk}} \cdot \frac{d}{dt} I_{dqs}^k + L_r \cdot \frac{d}{dt} I_{dqr}^k = -R_r \cdot I_{dqr}^k - \frac{N_r}{2} \frac{K_r}{K_s} \cdot \frac{K_{rk}}{K_{sk}} (\omega_k - \omega_r) \cdot j \cdot I_{dqs}^k - L_r \cdot (\omega_k - \omega_r) \cdot j \tag{32}$$

$$T_{em} = -\frac{L_m}{2} \cdot \sqrt{\frac{N_r}{3}} \frac{1}{K_s \cdot K_r \cdot K_{sk} \cdot K_{rk}} \operatorname{Im}\left(I_{dqs}^{k*} \cdot I_{dqr}^k - I_{dqs}^k \cdot I_{dqr}^{k*} \right) \tag{33}$$

From (31) to (33) is derived mathematical motor model. Derived motor model is described by equations (34) and (33).

$$L^k \frac{d}{dt} \begin{bmatrix} I_{ds}^k \\ I_{qs}^k \\ I_{dr}^k \\ I_{qr}^k \end{bmatrix} = \begin{bmatrix} U_{ds}^k \\ U_{qs}^k \\ 0 \\ 0 \end{bmatrix} - \left(R^k + L_w^k \right) \cdot \begin{bmatrix} I_{ds}^k \\ I_{qs}^k \\ I_{dr}^k \\ I_{qr}^k \end{bmatrix} \tag{34}$$

$$R^k = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \tag{35}$$

$$L_w^k = \begin{bmatrix} 0 & -\left(L_{1s} + \frac{3}{2}\cdot L_{ms}\right)\cdot\omega_k & 0 & -\frac{K_s}{K_r}\cdot\frac{K_{sk}}{K_{rk}}L_m\cdot\omega_k \\ \left(L_{1s} + \frac{3}{2}\cdot L_{ms}\right)\cdot\omega_k & 0 & \frac{K_s}{K_r}\cdot\frac{K_{sk}}{K_{rk}}L_m\cdot\omega_k & 0 \\ 0 & -\frac{N_r}{2}\cdot\frac{K_r}{K_s}\cdot\frac{K_{sk}}{K_{rk}}\cdot L_m\cdot(\omega_k-\omega_r) & 0 & -L_r\cdot(\omega_k-\omega_r) \\ \frac{N_r}{2}\cdot\frac{K_r}{K_s}\cdot\frac{K_{sk}}{K_{rk}}\cdot L_m\cdot(\omega_k-\omega_r) & 0 & L_r\cdot(\omega_k-\omega_r) & 0 \end{bmatrix} \tag{36}$$

$$L^k = \begin{bmatrix} \left(L_{1s} + \frac{3}{2}\cdot L_{ms}\right) & 0 & \frac{K_s}{K_r}\cdot\frac{K_{sk}}{K_{rk}}L_m & 0 \\ 0 & \left(L_{1s} + \frac{3}{2}\cdot L_{ms}\right) & 0 & \frac{K_s}{K_r}\cdot\frac{K_{sk}}{K_{rk}}L_m \\ \frac{N_r}{2}\cdot\frac{K_r}{K_s}\cdot\frac{K_{sk}}{K_{rk}}\cdot L_m & 0 & L_r & 0 \\ 0 & \frac{N_r}{2}\cdot\frac{K_r}{K_s}\cdot\frac{K_{sk}}{K_{rk}}\cdot L_m & 0 & L_r \end{bmatrix} \tag{37}$$

6 Induction motor with broken rotor bar

The equations above relate to healthy motor without faults. Rotor faults have got influence in resistivity $\mathbf{R}_{RR}$ and rotor inductance $\mathbf{L}_{RR}$ and mutual inductance $\mathbf{L}_{RS}$ or $\mathbf{L}_{SR}$.

A few methods are known about rotor fault modelling.

1) change of $\mathbf{R}_{RR}$ in the fault loops,

2) change of $\mathbf{L}_{RR}$ in the fault loops,

3) combination changes $\mathbf{R}_{RR}$ and $\mathbf{L}_{RR}$.

In the proposed paper is model with change of rotor resistance $\mathbf{R}_{RR}$. Advantage is possibility change fracture bar resistance. It permit simulate motor with partially break bar. If we consider break of rotor bar the resistance is higher but isn´t equal to ∞. The rotor bar current flows through laminated rotor core. In model is break bar resistance R_{bb} 10^4-times greater than healthy bar resistance. Change of $\mathbf{L}_{RR}$ is neglected.

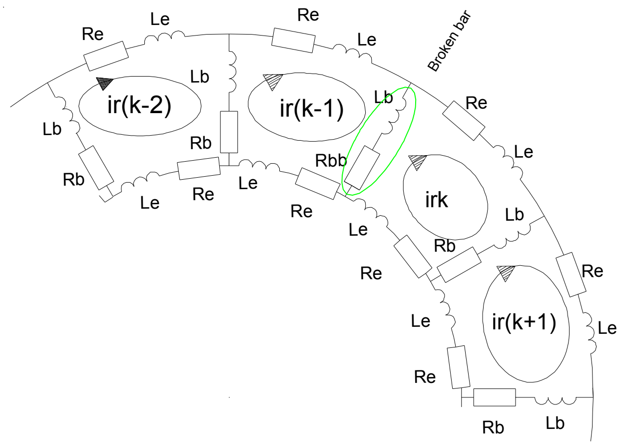

Figure 3 – Fault of rotor bar

Broken bar is marked in fig. 3. Equation for k-th loop is (38) and (k+1)-th loop in (39). These two loops are influenced by fracture. Resistivity from all loops can be written in matrix form (40).

$$0 = \left(R_b + 2R_e + R_{bb}\right)I_{r(k-1)} - R_b \cdot I_{r(k-2)} - R_{bb} \cdot I_{rk} + \frac{d}{dt}\Psi_{r(k-1)} \tag{38}$$

$$0 = \left(R_b + 2R_e + R_{bb}\right)I_{rk} - R_{bb} \cdot I_{r(k-1)} - R_b \cdot I_{r(k+1)} + \frac{d}{dt}\Psi_{rk} \tag{39}$$

$$\mathbf{R}_{RR} = \begin{bmatrix} R_0 & -R_b & 0 & 0 & \cdots & \cdots & \cdots & 0 & -R_b & -R_e \\ -R_b & R_0 & -R_b & 0 & \cdots & \cdots & \cdots & 0 & 0 & -R_e \\ \vdots & \ddots & \ddots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -R_b & 2R_e + R_b + R_{bb} & -R_{bb} & 0 & \cdots & -R_e \\ 0 & 0 & 0 & \cdots & 0 & -R_{bb} & 2R_e + R_b + R_{bb} & R_b & \cdots & -R_e \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -R_b & 0 & 0 & 0 & \cdots & \cdots & \cdots & -R_b & R_0 & -R_e \\ -R_e & -R_e & -R_e & -R_e & -R_e & -R_e & -R_e & -R_e & -R_e & nR_e \end{bmatrix} \begin{matrix} \\ \\ \\ * \\ * \\ \\ \\ \\ \end{matrix} \tag{40}$$

$*\,Modified \quad raw$

Change of the rotor resistance caused by bar fracture has a influence on the voltage decrease (41). New mathematical model with fault is in the equation (42). This equation is base for matlab model.

$$\Delta R_{dqr} I_{dqr}^k = e^{+j(\Theta_k - \Theta_r - \delta)} \cdot K_{rk} \cdot K_r \cdot \beta^{(k-2)}\left(1 - \beta\right)\left(R_{bb} - R_b\right)\left(I_{r(k-1)} - I_{rk}\right) \tag{41}$$

$$L^k \frac{d}{dt}\begin{bmatrix} I_{ds}^k \\ I_{qs}^k \\ I_{dr}^k \\ I_{qr}^k \end{bmatrix} = \begin{bmatrix} U_{ds}^k \\ U_{qs}^k \\ 0 \\ 0 \end{bmatrix} - \left(R^k + L_w^k\right) \cdot \begin{bmatrix} I_{ds}^k \\ I_{qs}^k \\ I_{dr}^k \\ I_{qr}^k \end{bmatrix} - \Delta R_{dqr} I_{dqr}^k \tag{42}$$

7 Induction motor model with break rotor bar

Heart of the model coming out from the equation (42) is in the figure 4. Motor motor model with parametres is enclosed in the end of this paper (files *Induction_Motor.mdl* and *Induction_Motor_Fault.m*). This model was utilized for description of the impact bar faults on the power spectral density.

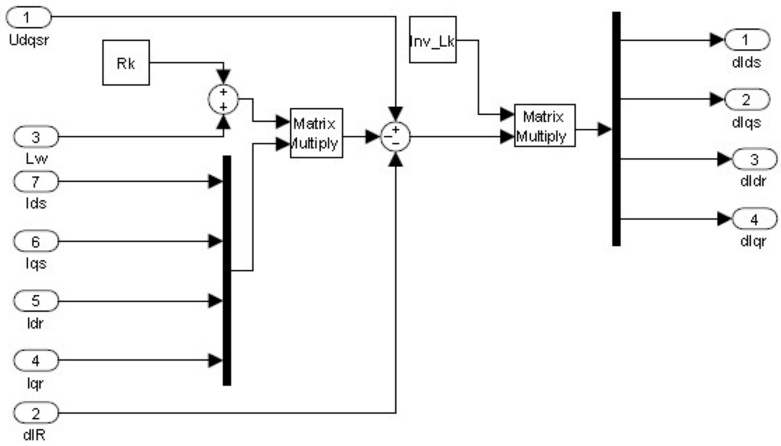

Figure 4 – Motor model acc. equation (42)

8 Spectrum analysis of machine

Motor is fed up by symetric harmonic voltage. The fed up frequency is f. In the Fourier spectrum healthy motor (fig. 5) is this frequency 50 Hz.

Break rotor bar bring in the spectrum new components. These spectrum components are in the table 1.

Table 1: Current spectrum - components

	Peak frequency [Hz] (Peak amplitude)										
Healthy motor	50 (28500)	-	-	-	-	-	-	-	-	-	-
1 broken bar	50 (27000)	31,33 (0,22)	38 (6)	44 (150)	56 (650)	62,3 (135)	68,33 (15)	74,56 (1)	-	-	-
2 broken bar	50 (27000)	36 (0,3)	38,33 (9,6)	42,33 (7,5)	43,66 (8,9)	58,6 (68)	59,33 (90)	60 (116)	60,66 (135)	61,66 (480)	73,66 (12)

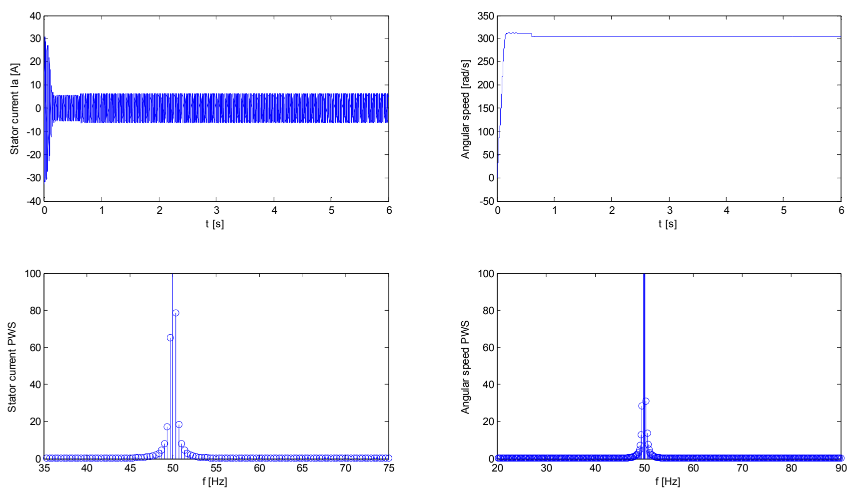

Figure 5 – Healthy motor, simulation result (stator currents and angular speed)

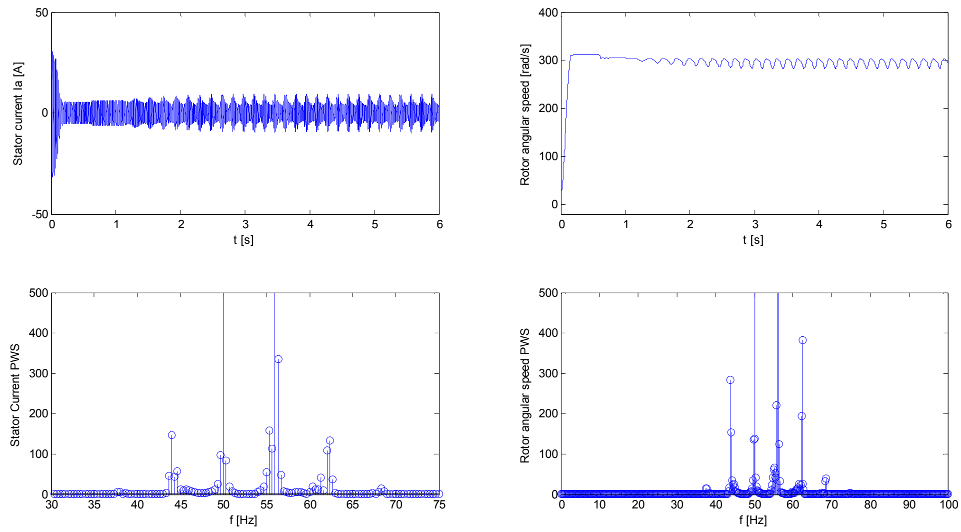

Figure 6 – Motor with one rotor bar fracture, simulation result (stator currents and angular speed)

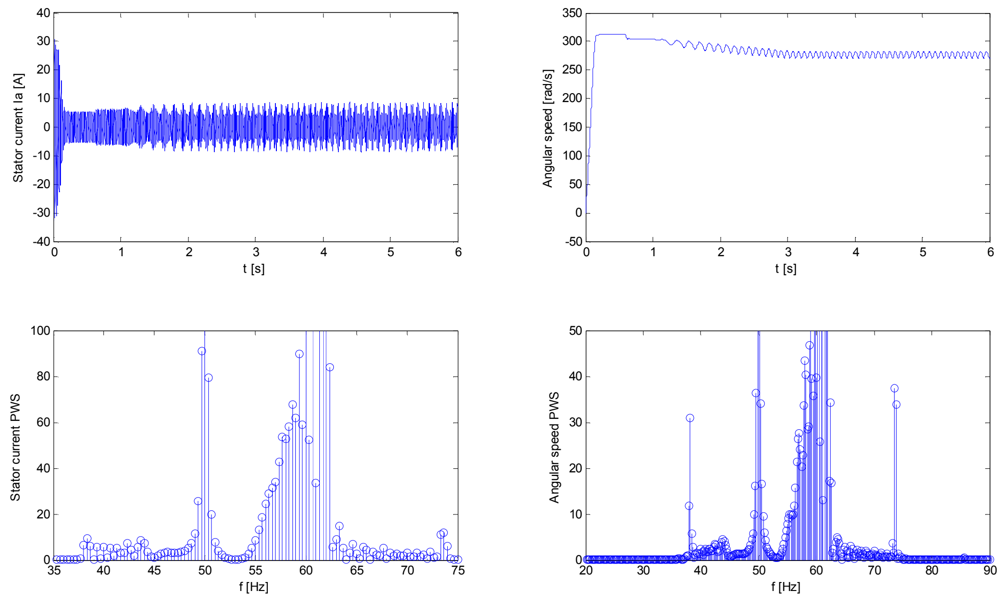

Figure 7 – Motor with two rotor bar fracture, simulation result (stator currents and angular speed)

9 Results

In this paper was described mathematical model of the induction motor and this model was transformed in the aplication Matlab Simulink. By using of this model was simulated behavior of the healthy motor, motor with one break rotor bar a with two break rotor bars. Using fast fourier transformation were investigated frequency spectra stator currents by different conditions.

Nomenclature

$\mathbf{U}_s = [u_{as}, u_{bs}, u_{cs}]^T$	– stator voltage vector ,
$\mathbf{I}_s = [i_{as}, i_{bs}, i_{cs}]^T$	– stator current vector,
$\mathbf{I}_r = [i_{r1}, i_{r2}, \ldots, i_{rN_r}]^T$	– rotor current vector,
$\mathbf{\Phi}_{ss} = [\varphi_{as}, \varphi_{bs}, \varphi_{cs}]^T$	– stator flux,
$\mathbf{\Phi}_{rr} = [\varphi_{r1}, \varphi_{r2}, \varphi_{r3}]^T$	– rotor flux,
J	– rotor moment of inertia
$\mathbf{L}_{sr}$	– mutual stator-rotor inductance
P	– number pole pairs
$\mathbf{R}_{ss}$, $\mathbf{R}_{rr}$	– stator and the rotor resistance matrixes
R_s	– resistance of stator phase a winding
R_e, R_b	– rotor end ring segment resistance, rotor bar resistance
R_{bb}	– break rotor bar resistance
L_e, L_b	– rotor end ring segment inductance, rotor bar inductance
L_s	– total inductance of the stator phase
l, g	– length of the rotor , air gap lenght
r , f	– air gap mean radius, stator supply frequency
T_e	– electromagnetic torque
T_L	– load torque
Θ_r	– rotor angular position
ω_r	– rotor mechanical speed
N_s	– number of stator windings
N_r	– number of rotor bars
I_{ds} I_{qs}	– direct and quadratic park current
ω_r	– permeability of air in the gap

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