Field-Circuit Analysis of Torque Pulsations of an Induction Machine under Inter-Turn Short Circuit

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The paper addresses a model of field-circuit induction machine, taking into account a failure of inter-turn short circuit of one of the phases of stator winding. The faulty state has been modeled with an implementation of an extra stator circuit winding. The paper looks into two machine states – one with a rated load and the other without it. For the machines states mentioned above, torque waveforms have been charted. The results obtained have been submitted for a spectral analysis. The relationships between inter-turn short circuits and torque pulsation have been stated on the basis of their analysis.

Index Terms— **Discrete Fourier transforms, Harmonic analysis, Fault diagnosis, Finite element methods, Induction motors, Rotating machine, Torque.**

I. Introduction

Research shows that nearly a third of failures in rotating motion electric machines is connected with a stator circuit failure, and thereby with an inter-turn short circuit issue [1].

This paper considers the influence of the number of inter-turn short circuits on torque waveforms of a machine both with a rated load and without it. The paper stresses the use of the obtained results in electric machines diagnostics applications.

II. Inter-Turn Short Circuit Modeling

The result of the inter-turn short circuit in a phase winding is a division of the phase winding into two parts (Fig. 1). The yellow part represents shorted turns has a number of turns equal to N_f, the resistance R_f and the inductance L_f.

Inter-turn short circuit affects many different parameters of the machine. For example, the effects of inter-turn short circuit can be observed in torque waveforms. In this paper the torque waveforms have been calculated using a field-circuit model of a machine. The field-circuit model consists of field equations which describe the distribution of a magnetic field, circuit equations which describe the connection of stator winding with the supply system, and the motion equation.
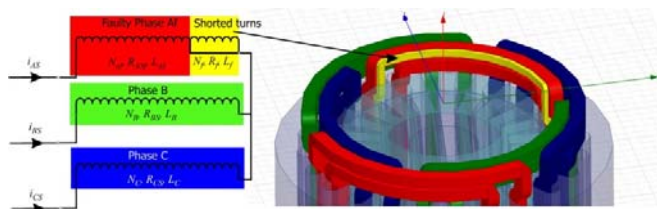

Fig. 1. Inter-turn short circuit modeling.

III. Selected Results of Calculations

Calculations were made for a squirrel cage induction machine. On the basis of the technical documentation of the tested machine, the FEM model of a machine was developed. The calculations were carried out in Maxwell computing environment. The level of machine damage was modeled by the changing of number of shorted turns N_f.

The waveforms of the torque during the start of the machine in the case rated load are shown in Fig. 2.
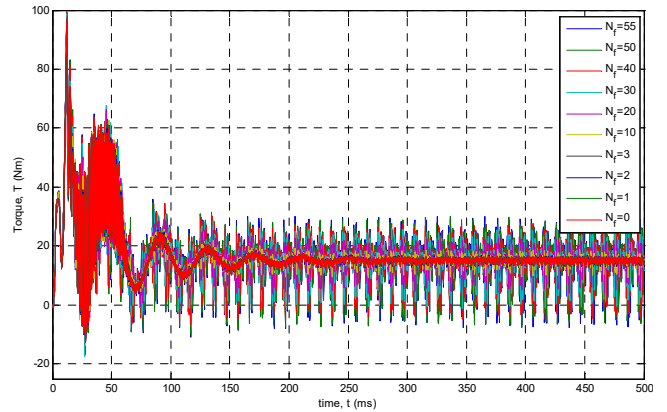

Fig. 2. Torque-time waveforms of a faulty machine at rated torque (T_L=15Nm).

A. Spectral analysis of the torque

A spectral analysis of the torque waveforms of a faulty machine was performed for a steady state. The results are shown in Fig. 3 and Fig. 4.
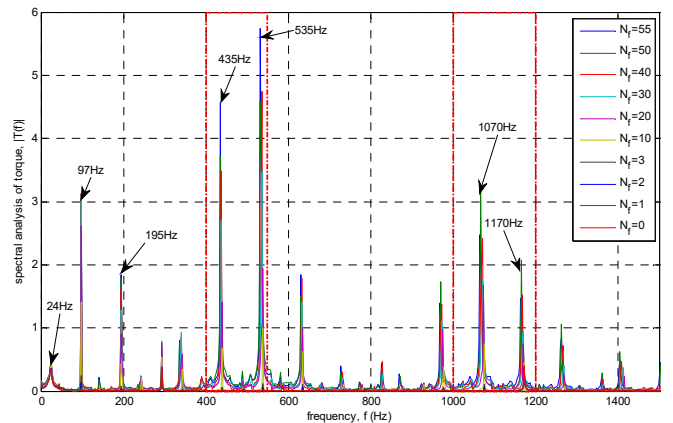

Fig. 3. Spectral analysis of the torque-time waveform of a faulty machine, at T_L=0Nm.
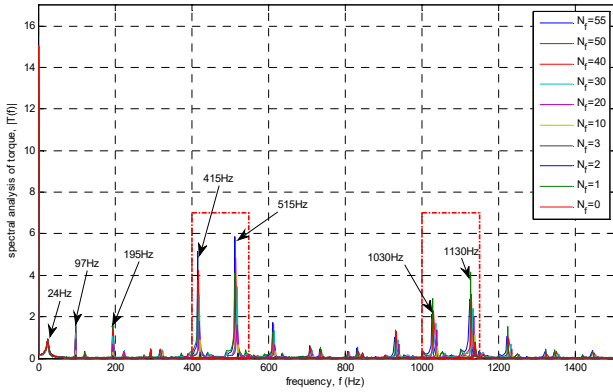
Fig. 4. Spectral analysis of the torque-time waveform of a faulty machine, at T_L=15Nm.

The results allow us to conclude that the effect of a shorted circuit on the torque waveform is very significant. Therefore, an attempt was made to determine the relationship between the number of turns and the torque pulsations. One of the many possibilities of reducing the torque pulsations is the fault-tolerant controller based on the indirect rotor field oriented control [4].

B. Torque oscillation factor

In the case of a machine without an external torque, the average value of the torque is almost equal to zero in a steady state. Therefore, the torque pulsations for a steady-state were calculated using the following formula

$$\Delta T = \frac{T_{\max} - T_{\min}}{2} \tag{1}$$

In the case of a machine at a rated torque, pulsations for a steady-state were calculated using the following formula

$$\Delta T = \frac{T_{\max} - T_{\min}}{T_{av}} 100\% \tag{2}$$

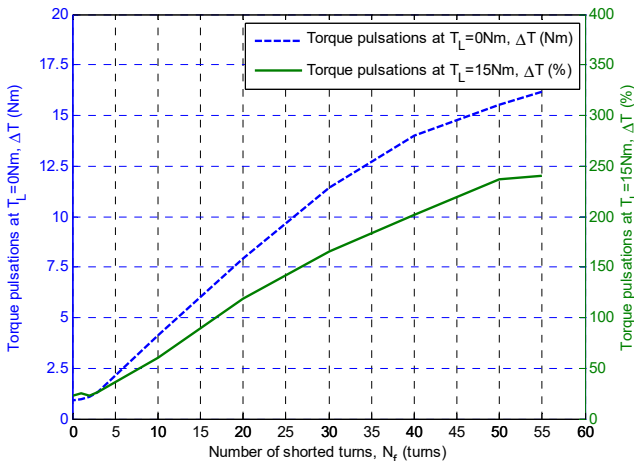The characteristic of torque pulsations ΔT versus the number of shorted turns N_f is shown in Fig. 5.

Fig. 5. Torque ripple factor as a function of shorted turns N_f in the case of a faulty machine, at T_L=0Nm and at T_L=15Nm.

It can be observed that the changes in torque pulsation are linear according to the changes of shorted turns.

The coefficient of determination indicates how well the calculations fit a linear equation. The interpretation of the value of R^2 is presented in Table I. The coefficient was calculated using following formula

$$R^2 = \frac{\sum_{i=1}^{n}\left(\Delta \hat{T}_i - \Delta \overline{T}\right)^2}{\sum_{i=1}^{n}\left(\Delta T_i - \Delta \overline{T}\right)^2} \tag{3}$$

where: $\Delta \hat{T}_i$ is the interpolated value of pulsations, $\Delta \overline{T}$ is the mean value of pulsations, ΔT_i is the calculated value of pulsations.

TABLE I. INTERPRETATION OF THE VALUE OF R^2

R^2	Interpretation
0.0 – 0.5	unsatisfactory fit
0.5 – 0.6	weak fit
0.6 – 0.8	satisfactory fit
0.8 – 0.9	good fit
0.9 – 1.0	very good fit

The R^2 coefficient calculation results are presented in Table II. Since the value of the coefficient is in the range of 0.9 – 1.0, it can be concluded that the relation between torque pulsations and the number of shorted turns is linear.

TABLE II. THE CALCULATED VALUE OF R^2

T [Nm]	Linear equation	R^2
0	$\Delta T = 0.327 N_f + 1.585$	0.9895
15	$\Delta T = 4.304 N_f + 21.079$	0.9885

IV. CONCLUSIONS

An algorithm for calculating induction machine torque waveforms at faulty states has been developed and presented in the paper. Based on the results obtained, a spectral analysis with the Fast Fourier Transform (FFT) has been carried out. Its results show the appearance of higher harmonics during inter-turn short circuit. The harmonics are $f(T_L=0Nm) = \{24, 97, 195, 435, 535, 1070, 1170\}$ Hz for the no-load machine, and $f(T_L=15Nm) = \{24, 97, 195, 415, 515, 1030, 1130\}$ Hz for the loaded one. Furthermore, a coefficient of determination has been calculated which allowed for further calculation of a torque pulsations coefficient. The results obtained may be used as an input vector of artificial neural network which is a decisive element of the diagnostic system [3, 4].

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