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DIAGNOSTIC SYSTEM FOR INDUCTION MOTOR STATOR WINDING FAULTS BASED ON AXIAL FLUX

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Abstract: The article presents the results of research on the use of an axial flux in the diagnostics of induction motor stator winding fed by a frequency converter. Voltage signal waveforms proportional to the axial flux were recorded during motor operation under various conditions and were analyzed with regard to the detection of stator winding short circuits. The taps of the selected coil turns of stator phases were introduced into the tested motor, which allowed to physical modelling inter-turn short circuits. The structure and operation of the computer system used to monitor the state of induction motor windings were discussed. The developed diagnostic system was made in the National Instruments LabVIEW environment. The analysis of faults of the axial flux was made in the detection of induction motor stator winding. The results of experimental research conducted using the developed diagnostic system have also been presented.

Keywords: *stator winding faults, inter-turn short circuits, axial flux, diagnostic system*

1. INTRODUCTION

A rapid development of technology has led to a significant increase in the size and the number of functions of automated technological lines in the manufacturing process. The reliability of these processes is one of the main criteria in the design of such lines. The main elements of technological lines are drive systems ensuring the motion of the operating parts of machinery. In industrial drive systems the highest proportion of all types of used motors are squirrel cage induction motors. The incorrect exploitation and construction errors in these machines may lead to their faults. According to the statistical data available in [1] over 32% of all analyzed faults were inter-turn short circuits. In a quarter of faulty machines there was a breakdown within a stator core. As shown in [1] 84% of faults in the analyzed induction motors occurred in the stator.

Contemporary diagnostics allows one to use numerous detection methods of stator faults. They are mainly divided with regard to the mathematical operation and the meas-

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urement signal used. Due to non-invasive measurements, the most commonly used diagnostic signals in the detection of inter-turn short circuits are phase current and mechanical vibration. The spectral analysis of stator current (motor current signature analysis) [2, 3] allows one to determine the degree of motor fault on the basis of the harmonic amplitude analysis of the current spectrum at frequencies characteristic of a given fault. However, variable load values exert a negative influence on the correctness of the detection process conducted with the use of MCSA, which constrains the use of this method [4]. The detection of inter-turn short circuits based on the signal of the phase-shift angle between the stator current and voltage [5–7] also strongly depends on the load. The analysis of the spatial vector module of stator current using EPVA (extended Park's vector approach) is devoid of all of these inconveniences [8, 9]. The EPVA analysis is confined to the observation of the shape and location of the obtained hodograph of the current vector. The foundation of this method are the spatial vector components of stator current calculated based on phase currents.

The analysis of axial (unipolar) flux allows the early detection of stator defects, which was presented, among others, in [10–12]. The idea of using the axial flux as a diagnostic signal was produced on the assumption that each electrical machine had certain asymmetries both magnetic and geometric, natural and created as a result of various types of faults. These asymmetries cause the occurrence of axial flux distribution generated by both the rotor and stator currents [13, 14]. The method allows one to measure the diagnostic signal in an easy and non-invasive way. The research on the efficiency of this diagnostic method [10, 12, 15] shows its applicability in the detection of both stator and rotor faults.

The article contains the results of investigations obtained using a developed diagnostic system in which the diagnostic signal carrying the information about electrical asymmetries caused by short circuits in stator winding was the axial flux. Chapter 2 discusses the influence of stator inter-turn short circuits on the axial flux signal. Chapter 3 provides the description of the developed monitoring and diagnostic system of short circuits. The results of experimental research and conclusions are presented in chapters 4 and 5, respectively.

2. INFLUENCE OF STATOR SHORT-CIRCUITS ON THE AXIAL FLUX OF THE INDUCTION MOTOR

Assuming the existence of an ideal three-phase induction motor fed by a symmetrical voltage source, one could presume that the axial flux does not exist. In practice, these assumptions could never be put into practice. As a result of the above, even in new, faultless machines it is possible to observe the phenomenon of creating the axial flux. The significance of this phenomenon can be influenced by both construction imperfections such as the diversity of materials used to make the motor structure, and faults occurring during machine operation. Short circuits of even a small number of stator windings contribute to the changes of the distribution of magnetic field spatial harmonic in the air gap slot. It is possible to detect time harmonics in the axial flux which occur along with spatial field harmonics. Voltage is induced in short-circuited windings and as a result there is a flow of current limited only by the self-impedance of short-circuited windings. The current flowing through the short-circuited windings is the source of magnetomotoric force pulsations which influence the spatial field harmonics [11].

There are two main methods of axial flux analysis for the purpose of stator inter-turn short circuit detection. A possibility of stator fault detection through the analysis of the RMS value changes of the voltage induced by the axial flux in the measuring coil has been presented in [12, 16]. As a result of the increase in the degree of stator winding fault, the value of the axial flux increases. A coreless coil with windings wound in perpendicular direction to the machine axis plays the role of secondary winding. Voltage induced in this coil results from the time-variable axial flux. The value of the axial flux is directly proportional to the voltage induced at winding ends. Hence, the change of the axial flux corresponds with the momentary value of the voltage induced in the measuring coil. The analysis of the state of induction machine stator winding is conducted by observing changes in the waveform of the induced voltage. The effectiveness of this method strongly depends on how the measuring coil is made and the selection of voltage measurement method.

The analysis of the axial flux spectrum, which is another method of detection stator inter-turn short circuits, has been presented, among others, in [14, 16]. In the spectrum, one can observe the increase in the amplitudes of slip frequency harmonics described by the following equation:

$$f_{sp} = kf_s \pm nf_s \frac{1-s}{p_b} \tag{1}$$

Equation (1) is frequently presented in a simpler form:

$$f_{sp} = kf_s - nf_r \tag{2}$$

where: k – order of supply voltage time harmonic, $n = 1, 2, 3, \ldots, 2p_b - 1$ and $n \neq 2p_b m$, $m = 1, 2, \ldots$, f_r – rotational speed of rotor [Hz], f_s – frequency of stator supply voltage [Hz], s – slip, p_b – number of pole pairs.

The above dependence defining the frequency of characteristic harmonics in the axial flux spectrum can be presented in the form of a table. The components which are of the highest significance in the diagnostics of stator winding faults are marked in Table 1 with a background. The distinguished components show the biggest amplitude changes in the axial flux spectrum. Usually the detection of stator winding faults is limited to the fifth and in special cases the seventh harmonic of the power source basic frequency [14].

Table 1. Frequencies of slip harmonics characteristic of inter-turn short circuits which can be observed in the axial flux spectrum in accordance with Eq. (1)

n	*k*					
	1		3		5	
	+	–	+	–	+	–
1	$f_s + f_r$	$f_s – f_r$	$3f_s + f_r$	$3f_s – f_r$	$5f_s + f_r$	$5f_s – f_r$
2	$f_s + 2f_r$	$f_s – 2f_r$	$3f_s + 2f_r$	$3f_s – 2f_r$	$5f_s + 2f_r$	$5f_s – 2f_r$
3	$f_s + 3f_r$	$f_s – 3f_r$	$3f_s + 3f_r$	$3f_s – 3f_r$	$5f_s + 3f_r$	$5f_s – 3f_r$
5	$f_s + 5f_r$	$f_s – 5f_r$	$3f_s + 5f_r$	$3f_s – 5f_r$	$5f_s + 5f_r$	$5f_s – 5f_r$

The developed diagnostic system uses fault symptoms observable in amplitude changes at slip frequencies, marked with bold frames in the Table. In addition to this, the amplitude changes of the axial flux spectrum were analyzed at frequency f_s and f_r.

3. METHODOLOGY OF THE RESEARCH

3.1. SHORT DESCRIPTION OF THE EXPERIMENTAL SETUP

The stator fault detection in the squirrel cage induction motor was conducted using the axial flux signal. The axial flux was determined indirectly by the measurement of voltage induced in the measuring coil positioned coaxially to the motor shaft next to bearings (Fig. 1).

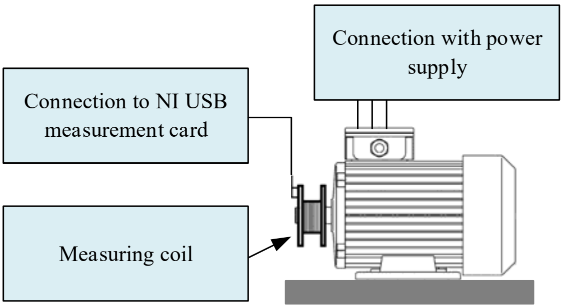

Fig. 1. Position of axial flux measuring coil

In the tested converter-fed induction motor of 1.5 kW, there were stator winding terminals used to physically model inter-turn short circuits (Table 1A in the Appendix presents the nominal data of tested motor). The number of terminals allowed for the short circuit of maximum 10 turns, i.e., over 3% of the total number of turns of one phase. During the research, 3 measuring coils with various numbers of turns and coil wire diameters were used. The coil signal was measured using a NI USB measurement card. The software environment was developed in the LabVIEW software.

3.2. DATA ANALYSIS AND DIAGNOSTIC SOFTWARE SPECIFICATION

The computer system for monitoring and diagnosing the state of induction motor stator winding was developed in the National Instruments LabVIEW environment. During the experimental verification of the diagnostic system, the application worked correctly on a National Instruments industrial computer, a traditional PC, and a laptop.

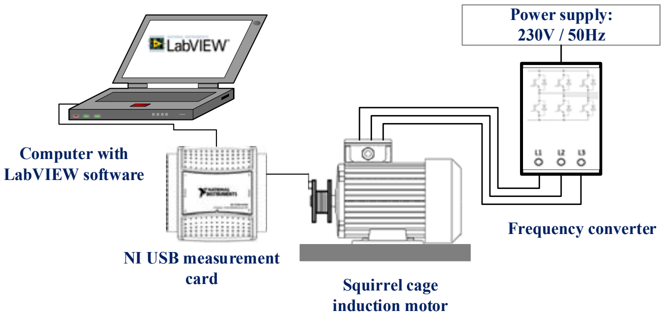

Fig. 2. Scheme of the measurement system for testing the stator winding faults of the induction motor

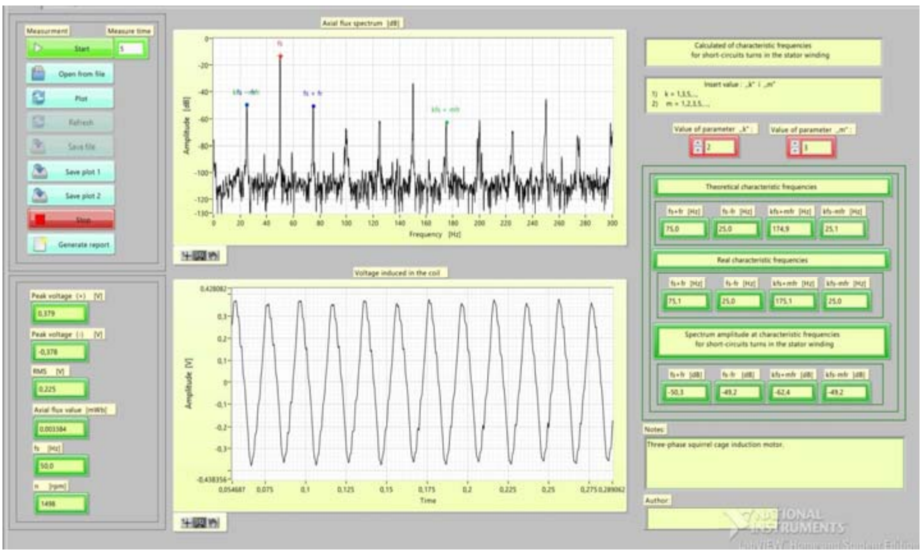

Fig. 3. Diagnostic software for the stator winding fault testing – the operator panel

The advantage of the newly developed system is the possibility to record the diagnostic system using any measurement card working with the LabVIEW environment. The computer system and the measurement card were connected with each other through a USB port. The schematic diagram of the measurement system is presented in Fig. 2.

The proposed diagnostic system was to measure the signal of voltage induced in the measuring coil and to process it for the purpose of simple detection of inter-turn short circuits. In order to single out the information necessary for correct diagnostics based on the measurement signal, the software used FFT (fast Fourier transform). As a result, the obtained signal spectrum was a graphic representation of the signal frequency characteristic. The diagnostic system was composed of two parts: operator panel simulating the faceplate of the measurement device used with the software and a block diagram responsible for the logical part of the software. The operator panel is presented in Fig. 3.

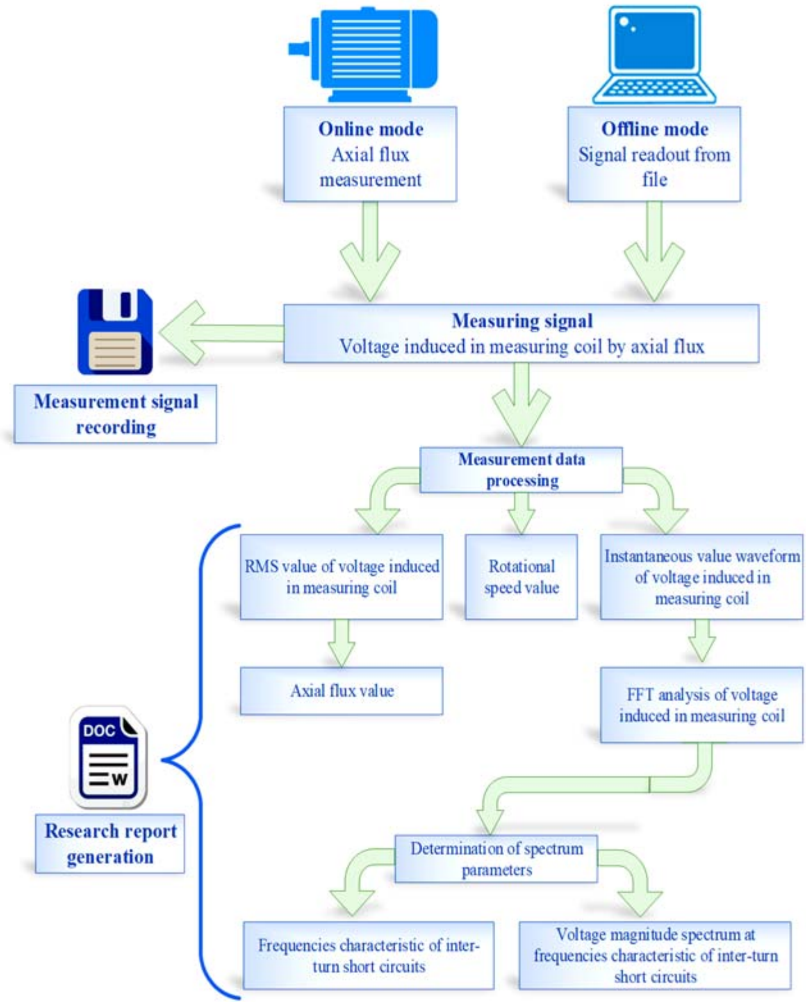

Fig. 4. Concept of the computer diagnostic system of induction motor stator winding faults

The operator panel was divided into 3 parts:

1. Measurements, savings as files and read-outs.
2. Display of the waveform of the voltage induced in the coil.
3. Display of the parameters of the induced voltage spectrum.

The first part of the system allows one to select the parameters of the analyzed signal and signal registration. The advantage of this program is the possibility to reproduce the previously recorded measurement signals, saved automatically as text files. The reproduction and the registration of induced voltage waveforms allow one to conduct the comparative analysis of the motor condition at various stages of the fault. The diagnostic system also generates a detailed report of the conducted tests. The second part is responsible for displaying the waveform of the voltage induced in the coil. As was presented in [16], changes in voltage waveforms and their RMS values may indicate a stator fault. The developed diagnostic system uses two detection methods of inter-turn short circuits, the analysis of the RMS value of the induced voltage, and the analysis of changes in the axial flux spectrum. The third part allows one to display the spectrum waveform of the voltage induced in the measuring coil. When a user gives parameters k and n in Eq. (2), the spectrum is searched in order to mark the maximum amplitude values at slip frequencies characteristic of a given fault. Figure 4 presents the block diagram of the concept of the computer system for monitoring the induction motor stator winding.

4. ANALYSIS OF EXPERIMENTAL RESULTS

The experimental verification was conducted for a converter-fed induction motor, 1.5 kW, INDUKTA Sh90L4. The measurements were taken with the developed diagnostic system using the axial flux measurement. The waveforms of voltage induced by the axial flux and its spectra have been determined. The research consisted of the following stages:

1. Determination of voltage induced in a measuring coil for various numbers of turns in stator winding. Short circuits were realized in one phase of the induction motor stator at constant supply voltage frequency of 50 Hz.
2. Determination of the influence of supply voltage frequency changes on inter-turn short circuit detection. The tests were conducted for the voltage frequency changes in the range of 10–50 Hz.
3. Determination of the influence of motor load changes on the detection of inter-turn short circuits. The measurements were taken for an unfaulty motor and a motor with 8 shorted turns in one phase while the load was gradually increased.
4. Determination voltage waveforms with gradual shorting of an increasing number of turns. The supply voltage frequency during the tests was 50 Hz. The measurements were taken so as to show the change of the RMS voltage upon increasing the fault degree of the stator winding of the induction motor operating on-line.

Figures 5, 6 present the axial flux spectrum in the case of the unfaulty motor and the motor with 10 shorted turns in one phase. For the purpose of comparing spectra, in the figures, the characteristic harmonics of inter-turn short circuits were marked. The presented results show that inter-turn short circuits in the stator of the squirrel cage induction motor result in a significant increase in the value of nominal harmonic amplitude. With 10 shorted turns, the amplitude increased by about 62% in comparison with that of the unfaulty motor.

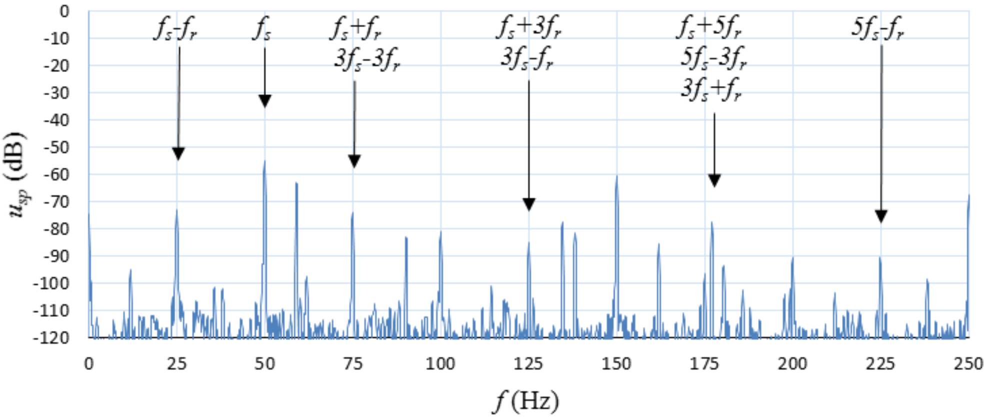

Fig. 5. Spectrum of the voltage induced in the measuring coil for an unfaulty motor

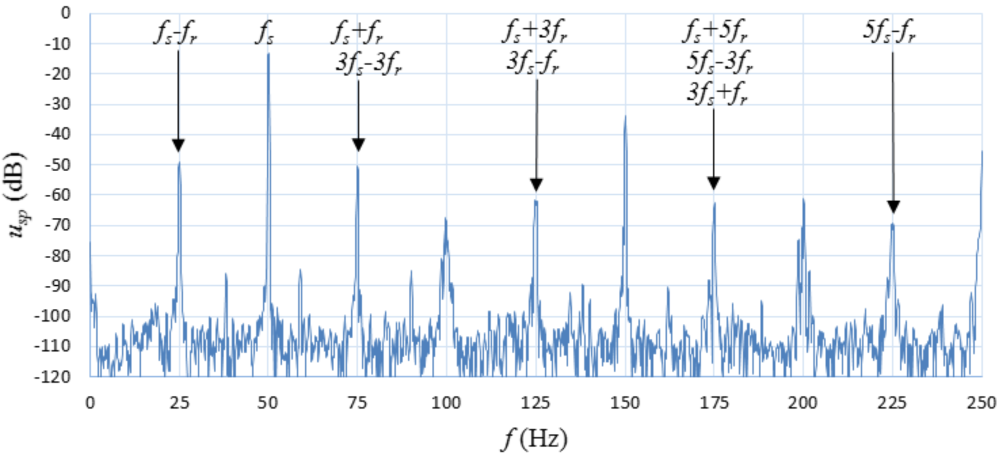

Fig. 6. Spectrum of the voltage induced in the measuring coil for the motor with 10 shorted turns in phase A; motor supplied with the nominal frequency voltage

The detection of inter-turn short circuits can also be conducted through the analysis of the amplitudes of characteristic frequencies. The increase in amplitudes at slip frequencies which have the greatest significance in the diagnostics of inter-turn short circuits (Table 1) is on average 20 dB higher for 10 shorted turns. A considerable growth is also observable at frequencies being odd multiplicities of the supply voltage harmonic. Figure 7 presents the dependence of the voltage magnitude spectrum at frequencies characteristic of inter-turn short circuits on the number of shorted turns.

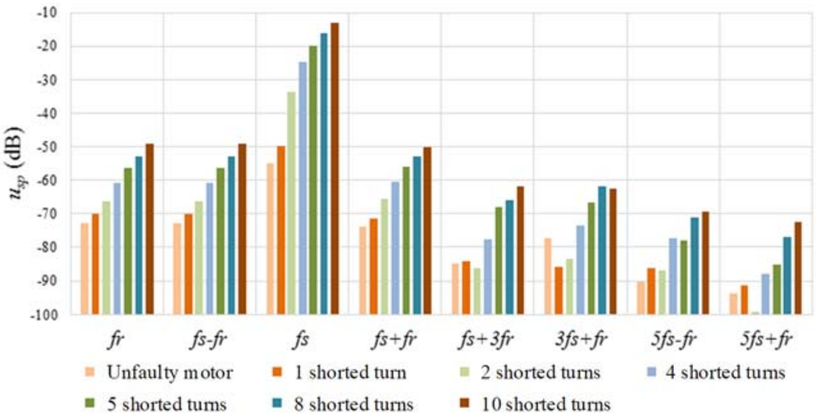

Fig. 7. Dependence of the voltage magnitude spectrum (corresponding to the axial flux) for various characteristic frequencies on the number of shorted turns in the stator winding

In diagnostics, the most considerable significance lies in these frequencies in the spectrum which show the greatest changes in amplitude. In accordance with the results of the research, the detection of inter-turn short circuits in the squirrel cage induction motor may also take the form of the analysis of frequency amplitudes $f_s - f_r$, f_s, $f_s + f_r$, $f_s + 3f_r$, and $5f_s - f_r$. A change of the basic harmonic allows one to observe a short circuit at level 1 of a shorted turn. It is also possible to observe a rapid increase of the amplitude at the initial stage of a fault (up to 4 shorted turns). Next this increasing tendency weakens as the fault increases. The amplitudes distant from the network harmonic by the value of the rotational frequency of the rotor also show an increase when only 1 turn is shorted.

Figures 8 and 9 present the dependence of the voltage magnitude spectrum for various characteristic frequencies on the supply voltage frequency of the motor. Figure 8 shows the range of the analyzed spectrum decreasing with reducing frequency. The influence of voltage magnitude spectrum on the supply voltage frequency for 10 shorted turns is presented in Fig. 9.

Upon increasing supply voltage frequency, one can observe the growing influence of interference in the voltage spectrum (Fig. 8). There is also a problem with monitoring the state of the machine due to the deformation of measurement signals. As a result of the decreasing supply voltage frequency, the amplitude value at frequencies characteristic of shorted turns declines (Fig. 9). Their change is proportional to the change of supply voltage frequency. The reduced values of these amplitudes significantly hinder the quick and correct fault detection in stator winding. Such a change influences the speed of the detection process, however, it does not make it impossible.

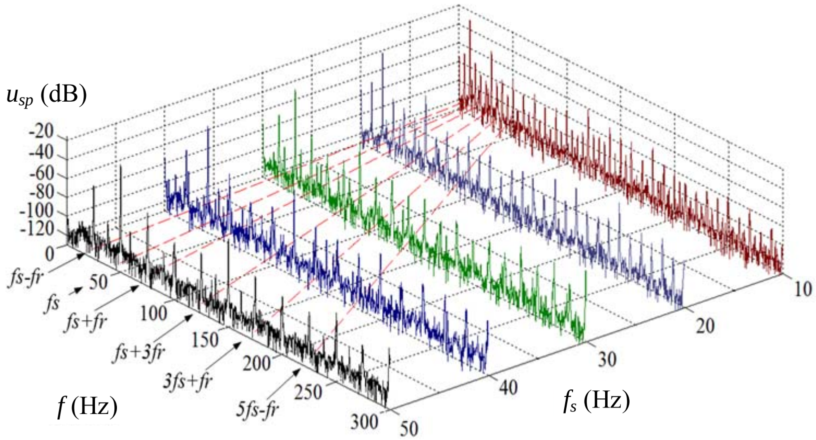

Fig. 8. Dependence of the voltage magnitude spectrum (corresponding to the axial flux) for various characteristic frequencies on the supply voltage frequency – faulty motor, unloaded

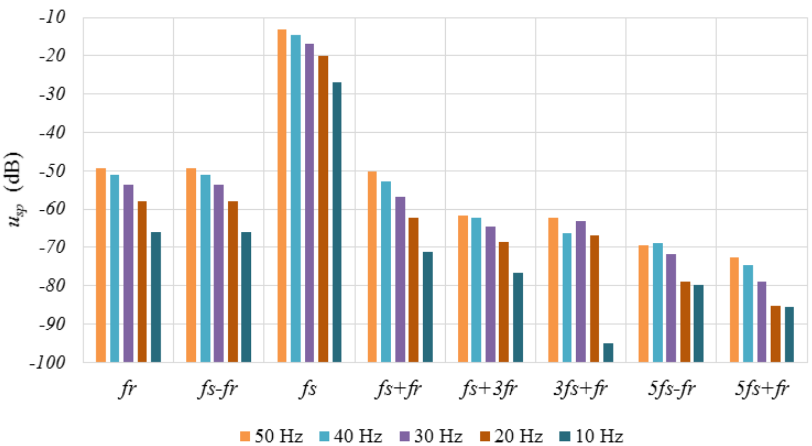

Fig. 9. Dependence of the voltage magnitude spectrum (corresponding to the axial flux) for suitable characteristic slip harmonics on the supply voltage frequency – faulty motor (10 shorted turns)

Next the subject of analysis was the possibility of inter-turn short circuit detection using the axial flux measurement, with changing motor loads, the results are presented in Figs. 10 and 11. In the case of an unfaulty motor, one can observe that the values of these amplitudes increase upon increasing load. When there is a fault in the stator winding, the amplitudes at frequencies characteristic of inter-turn short circuits are constant.

Hence, one can conclude that the motor load does not inhibit the detection process. The developed diagnostic system using the axial flux measurement can be used in a motor with a constant torque load, fed by nominal frequency voltage.

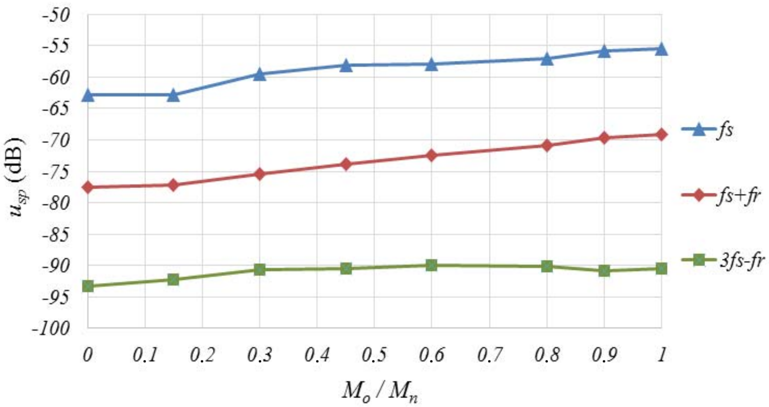

Fig. 10. Dependence of spectrum amplitudes for particular characteristic frequencies on motor load – unfaulty motor, f_s = 50 Hz

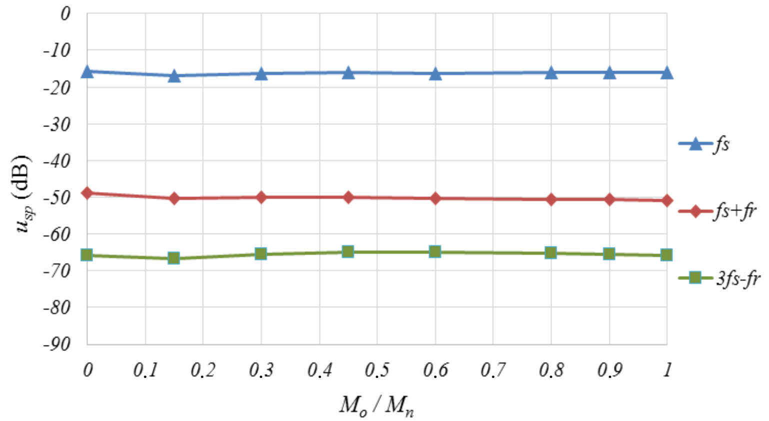

Fig. 11. Dependence of spectrum amplitudes for particular characteristic frequencies on the motor load – faulty motor (8 shorted turns), f_s = 50 Hz

The use of only the voltage magnitude spectrum analysis for voltage induced in the measuring coil allows one to detect short circuits even at the level of two shorted turns. When only one turn was shorted in phase A, no visible voltage waveform changes were observed. The RMS value of voltage when there is 1 shorted turn is higher by only 1 mV than the RMS value of the unfaulty motor. For comparison, when 2 turns are shorted the same change is 10-fold bigger and in the case of 10 shorted turns – 100-fold bigger.

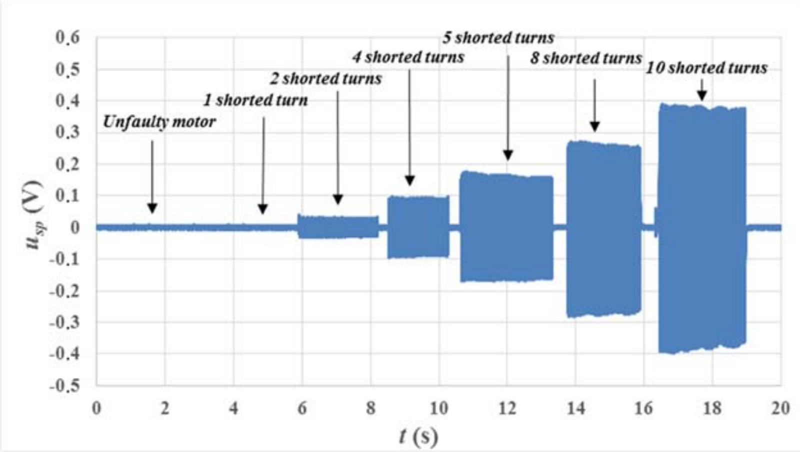

Fig. 12. Dependence of the voltage magnitude spectrum (corresponding to the axial flux) on the stator winding fault level of the induction motor

5. CONCLUSIONS

The effectiveness of the use of axial flux in induction motor diagnostics has been shown. The analysis of the axial flux spectrum provides information on inter-turn short circuits in the motor stator even at an early stage of this fault. The advantage of this method is its simple measurement-diagnostics system without necessity to use measurement signal transformers. The early recognition of a fault in stator winding enables one to plan a possible repair. This is important with regards to the type of fault. Inter-turn short circuits develop very quickly starting with one turn and then, under the influence of increased currents, faults occur in subsequent turns. The fault spreading speed is influenced by the motor power supply. The frequency converter power supply has significant impact on the turn insulation degradation, which is caused by the character nature of voltage. The power supply source, similarly to the motor load, is observable during short circuit detection, however, it does not influence the diagnostic process. The proposed diagnostic system for stator winding faults uses the axial flux because of the low invasiveness of the measurement and the possibility of the early detection of inter-turn short circuits, and as a result it can make an alternative for commonly used systems in the measurement diagnostics of phase currents and mechanical vibrations.

APPENDIX

Table 1A. Rated parameters of tested induction motor

Parameter	Value
Power, P_N	1500 W
Torque, M_N	10.16 N·m
Speed, N_N	1410 r/min
Stator phase voltage, U_{sN}	230 V
Stator current, I_{sN}	3.5 A
Frequency, f_{sN}	50 Hz
Pole pairs, p_p	2
Number of rotor bars, N_r	26
Number of stator turns in each phase, N_s	312
Stator resistance, R_s	5.307 Ω
Rotor resistance, R_r	4.843 Ω

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