ANALYSES OF SHAFT CURRENTS IN LOW-VOLTAGE INDUCTION MOTOR FOR FORKLIFT DRIVE WITH ELECTRONIC EQUIPMENT

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Key words: low-voltage induction motor, shaft currents, measurements, electronic equipment

Abstract: At the power supply of the low-voltage asynchronous motors (with homogeneous yokes) from the network, shaft currents resulting in damage of bearings, can emerge. The main cause of these currents is the eccentric position of rotor in the stator bore (static and dynamic eccentricity). The required condition for the emergence of these currents is nonlinearity of magnetizing curve of electrical steel of the motor stack lamination. The article describes performed measurements on the four-pole motor. First, the measuring equipment: Rogowski coil and his mounting, AD converter NI-DAQPad-6015 and power analyzers NORMA-D6000 have been described. Then, ways of measurements and processing of measurements have been explained. Data obtained by measurements have been presented at the nominal load, for the star- and delta-connected stator winding, measured with AD converter NI-DAQPad-6015 and power analyzer NORMA-D6000. Differences in measured results of shaft currents measured by the power analyzer NORMA-D6000 related to measurements with the AD converter NI-DAQPad-6015 are explained.

Analiza meritev tokov gredi nizkonapetostnega asinhronskega motorja za pogon viličarja z elektronsko opremo

Kjučne besede: nizkonapetostni asinhronski motor, tokovi gredi, meritve, elektronska oprema

Izvleček: Pri napajanju nizkonapetostnih asinhronskih motorjev (s homogenimi jarmi) iz omrežja lahko nastanejo tokovi v gredi, ki imajo za posledico okvaro ležajev. Glavni vzrok teh tokov je ekscentrični položaj rotorja in statorja (statična in dinamična ekscentričnost). Potrebni pogoj za nastanek teh tokov je nelinearnost magnetilne krivulje materiala - lamel paketa, tj. dinamo pločevine motorja.

V članku so opisane izvedene meritve na štiripolnem motorju za pogon viličarja. Najprej je opisana merilna oprema: tuljava Rogowskega in njena vgradnja, AD kartica NI-DAQPad-6015 in digitalni analizator NORMA-D6000. Nato so pojasnjeni načini meritev in predvsem obdelava meritev.

Za izvedene meritve so prikazani rezultati meritev v nazivni točki, za vezavo zvezda in trikot statorskega navitja z AD kartico NI-DAQPad-6015 in inštrumentom NORMA-D6000. Pojasnjene so razlike merilnih rezultatov za vrednosti tokov gredi pri merjenju z AD kartico NI-DAQPad-6015 glede na meritve z analizatorjem moči NORMA-D6000.

1. Introduction

The phenomena of shaft currents at big synchronous and induction machines was discovered and explained in the last century. Air gaps in the stator yoke that exist in the stator stacks put together from parts (segments) or completed stacks composed of steel segments can cause shaft currents. They are closed in the circuit: shaft - bearing - bearing shield - housing - bearing shield - bearing - shaft and they damage the bearings.

The mechanisms of the shaft currents beginning at low voltage induction motors that have as a rule homogeneous yoke are very complicated /1/. In this article it is presented that the nonlinearity of magnetization curve of iron is a necessarily condition of the shaft currents origin.

All manners of shaft currents origins at low voltage induction motors are not explained to the end, therefore it is necessary to determine, from the view of the shaft current measurements, with frequency analyses the harmonic content of the shaft currents and then to determine the ground as well as the mechanism of the harmonic components origin.

In this article the measurements of shaft currents on one four pole low voltage induction motor with the help of Rogowski coil /2/ are analyzed. The method of shaft currents measurements with Rogowski coil is recommended in /3/, where Rogowski coil was mounted around the shaft of the rotor.

At shaft current measurements described in /4/ the Rogowski coil was mounted (around the shaft) on the stator and at measurements described in this article the Rogowski coil was also placed on the stator.

At the end it should be reminded that we may not mistake the notion of the shaft currents with the notion of the bearing currents that are closed thru the bearings without regard to mechanism of the origin and of the currents frequency. The shaft currents begin by supply of the motor from the network and should be named "inductive", but important harmonic components of these currents are in the range form 0 to 1000 Hz. At the supply from the frequency converter except low and high frequency shaft currents (Circulating Bearings Currents), therefore "inductive" currents also the "capacitive" bearing currents, begin. Characteristic high frequency of "inductive and "capacitive" harmonics currents components in dependence of the control and realization of the converter and motor may exceed 100 kHz.

The consequences of the difference of the shaft currents are necessarily the different ways in the calculation (different machine models) and measurements of these currents. The subject of this article are the measurements of the shaft currents by supply of the low voltage induction motor with squirrel cage from the network.

2. Measuring equipment for shaft currents

By measurements of the shaft currents, the standard performance Rogowski coil AmpFLEX A100 20/200 A, is used and for data assembling from the Rogowski coil two parallel devices are used: AD card NI-DAQPad-6015 and power analyzer NORMA-D6000. Parallel with the shaft currents measurements on two different ways the stator currents of the motor were measured with the help of: Rogowski coil and (AmpFLEX A100 20/200 A) and by using current shunts (Triaxial shunt 6 A...300 A).

AmpFLEX A100 20/200A is a coil of Rogowski with flexible air core, of the extent of 45 cm, produced by Chauvin Arnoux which enables the measurements of alternating currents to 200 A. The coil has two measurement ranges: to 20 A with output voltage ratio 100 mV/A and to 200 A with output voltage ratio 10 mV/A. The accuracy of the measurements is 1 % from 10 Hz to 20 kHz frequency range and angle error 1°; the output impedance is 1 kΩ.

At measurements of the shaft currents the Rogowski coil is placed in the inner space of the bearing shield of the motor in such a manner that it symmetrically embrace the bearing and the shaft is perpendicular on the area by which the Rogowski coil is closed (Figure 1.), that is essentially for the accuracy of the measurements /2, 5/.

At low voltage induction motors the distance between winding overhang and the bearing edge is only some centimeters. The vicinity of the stator winding and the Rogowski coil is the reason why the additional shaft current is meas-

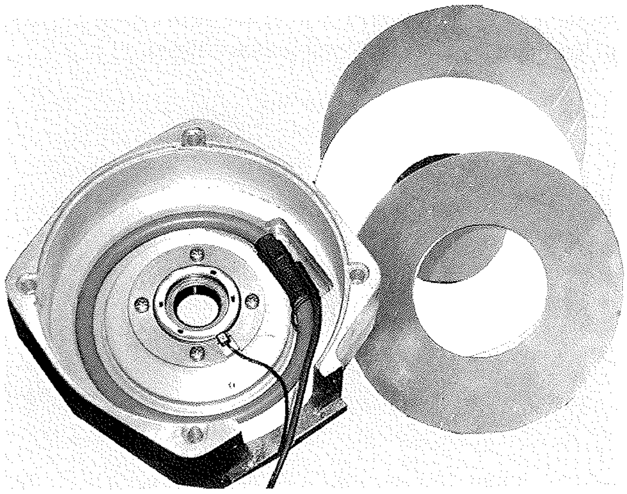

Fig. 1. Bearing shield with Rogovski coil and magnetic screen from two iron sheets and isolation

ured by the coil owing to leakage flux of the winding overhang, which size by the observed motor is approximately equal to the shaft current. To assure the correct shaft current measurements by Rogowski coil it is necessary to avoid the influence of the winding overhang leakage flux on the measured current size.

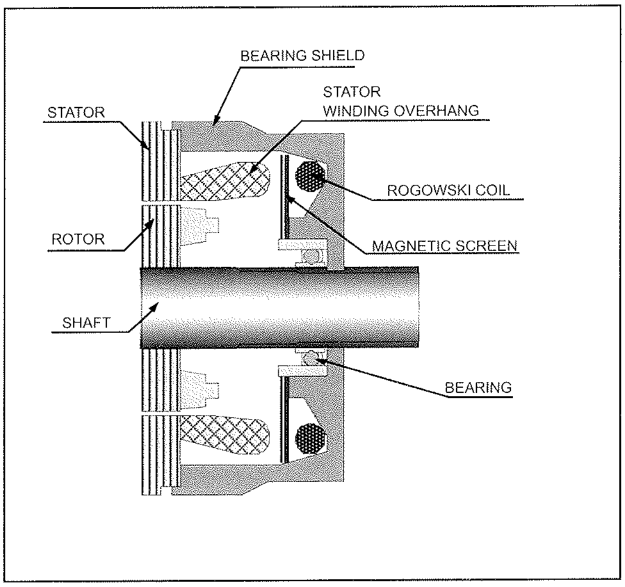

Fig. 2. Position of Rogowski coil and magnetic screen inside of the motor

With the intention to prevent the leakage flux breakthrough into the Rogowski coil two iron sheets 1mm thickness are mounted, they are galvanic separated between each other (Figure 2.). With insertion of such magnetic screen the leakage flux from winding overhang is chocked to the level that is smaller then quantum noise (Figure 3.). Then the voltage signal from the Rogowski coil, which represents the contribution of the leakage flux of the stator winding overhang, has the smaller size than the reading resolutions (equation (7) in chapter 3. The method of measurements) and after the AD conversion the signal size of the disturbance could not differentiate from the error owing to round up the sample on the nearest quantum level.

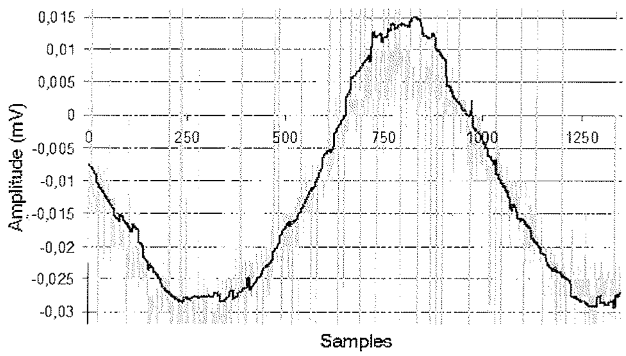

Fig. 3. Voltage output form card NI-DAQPad-6015 by determination test of winding overhang leakage influence on the disturbances from Rogowski coil (at rated current and without rotor)

NI-DAQPad-6015 is an AD card of the producer National Instruments, which enables simple connection (plug and play) with PC via USB connector with maximum sampling frequency of 200 kS/s. The card has 16 analog inputs, 8 digital I/O, 2 analog outputs and all connectors are BNC type. The characteristics of the devices is 16 bits accuracy and the voltage range of the card is ±0,05 V (resolution 1,52 μV) to ±10 V (resolution 0,305 μV). The AD card assembled data from four Rogowski coils. One measured shaft current but three measured stator currents of the motor. The voltage output from the Rogowski coil integrator was of the span-width ±3 V and so is this selected voltage range of the measured device. The AD card doesn't have his own memory, so the data in the real time measurement via USB are transmitted in the PC where they are adjusted and stored by the help of the program package LabVIEW.

NORMA-D6000 is the power analyzer suitable for all measurements of the motors and generators. Beside of the current and voltage measurements, simultaneously the torque, speed, mechanical power and slip (together 12 input channel) could be measured. The high accuracy makes possible the precisely determination of the losses. The device has its own memory and it is possible to make FFT analysis of the measured signals on the site. With the analyzer the data about shaft currents from the Rogowski coil, stator current of the motor which is measured with the help of the current shunts, further about the motor speed, torque on the shaft and the stator voltage of the motor are collected. All data are simultaneously collected and stored in the device memory and from there the measurements are than transmitted into the PC. The current and voltage channels have the accuracy: ± (0,05 % from the measuring range, +0,02 % from measuring magnitude), therefore this instrument may be used in the lab test. Owing to the relative small voltage signal from the Rogowski coil (which measured the shaft currents) into the ratio to the smallest voltage range of ±25 V in the measured signal a 20 dB bigger noise as at AD card was present, which had the voltage range of ±3 V.

3. Method of measurements

Shaft currents measurements demand fulfilling of some conditions so that later quality frequency processing of the measured signal would be realized. Before the beginning of the measurement it is essentially to determine the frequency range, common measured time of the signal (T_s), number of samples in this time (N), as well as the resolution of the measured signals.

By shaft current measurement the frequencies of some important harmonic component should be expected in the range from 0 to 1000 Hz. From the Nyquist theorem of sampling of signals

$$f_N \geq 2 \cdot f_{max} \quad (1)$$

it follows that the sampling frequency (f_N) must be at least twice as big as the maximum frequency (f_{max}) that should be expected, therefore it is necessary to do the measurement with more than 2000 samples in one second. Further, that in the FFT analyses it should be possible to differentiated frequencies in the range of the 0,1 Hz (frequency resolution Δf), it follows that by the equation

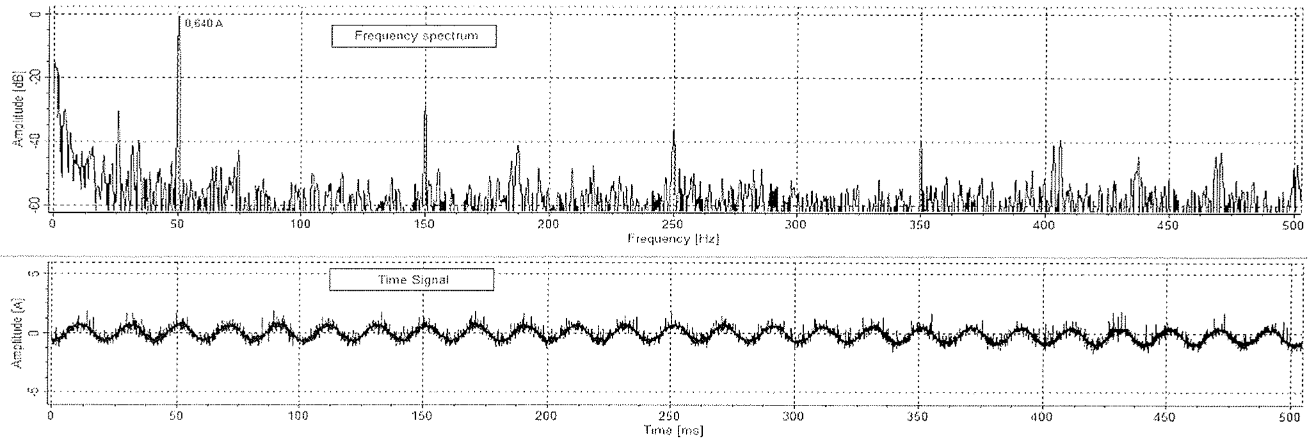

Fig. 4. Shaft current in Y connection (NI-DAQPad-6015) – frequency specter and time signal

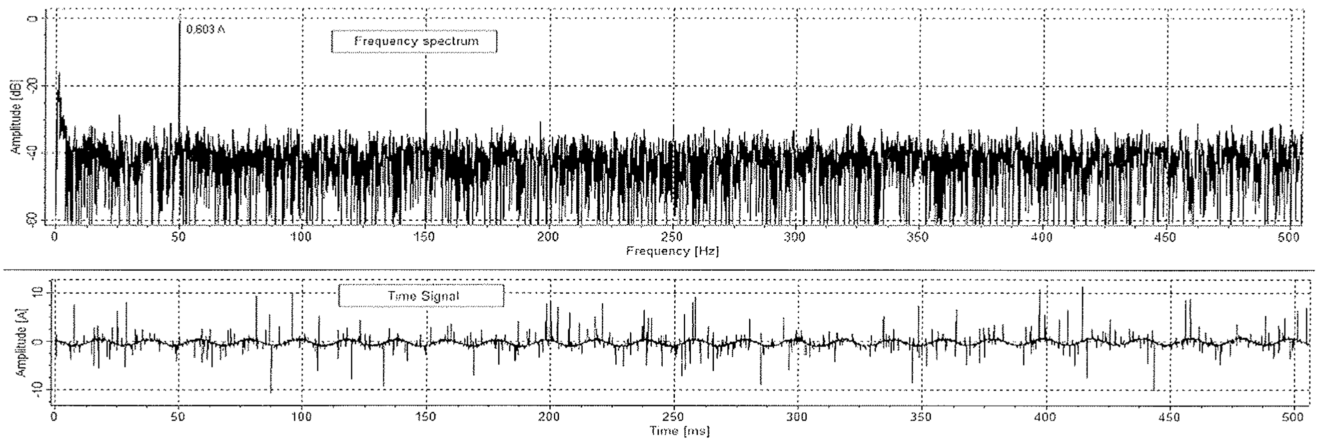

Fig. 5. Shaft current in Y connection (NORMA-D6000) - frequency specter and time signal

$$T_s = \frac{1}{\Delta f} \qquad (2)$$

sufficient common measured time of the signal (sampling time) is 10 second.

The ratio between the sampling time and the number of the samples in this time is called the time resolution (Δt) and it represents time displacement between two samples

$$\Delta t = \frac{T_s}{N} \qquad (3)$$

The signal, which is processed by the DFT/FFT analysis, has limited time interval but it has to represent the signal of the infinite duration i.e. the supposition is that the observed interval has the periodical repetition and so the infinite duration signal is formed. This leads in the FFT analysis to the error and to the phenomena of the artificial frequencies which result in the spectrum - leakage. The leakage is manifested so that beside existent harmonic components in the original signal, after the frequency treatment, harmonic components appear which are not in the original signal. In the specter this leads to: appearance of increased noise, by which the less expressed harmonics are covered, or decrease of the amplitude of the salient harmonic components.

With the aim to decrease the leakage in the DFT/FFT analysis, filters called windows /6/ are used to be applied as the standard. Practically many types of the windows exist, but two types represent the extremes: Hanning's because of the simplicity of the algorithm is mostly used and Blackman's, which gives smaller leakage, bigger accuracy of the amplitude defining but it needs more memory space as Hanning's windows. By all types of windows their influence has improved with reduced resolution of the signal and this can be achieved in the given time of the sampling signal (T_S) by increasing in relation to (3).

The number of the samples (N_S) in the time of sampling (T_S) is called a sampling rate and represents the reciprocal value of the time resolution

$$f_s = \frac{1}{\Delta t} \qquad (4)$$

The sampling rate is limited by the possibility of measuring equipment. For data sampling at measured equipment two parallel devices are used: NI-DAQPad-6015 in NORMA-D6000.

The Card NI-DAQPad-6015 has upper boundary sampling rate f_{smax} = 200 kS/s (number of the samples in the sec) and this value is reduced reciprocal proportionally with the

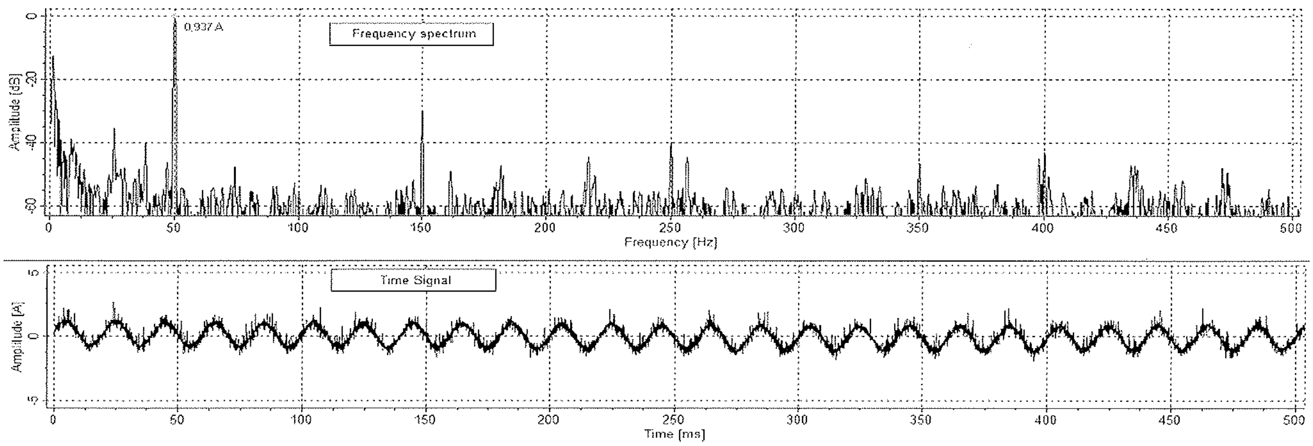

Fig. 6. Shaft current in Δ connection (NI-DAQPad-6015) - frequency specter and time signal

number of the input signals, owing to the transmission of data via USB in the PC. Regarding to $n_i = 4$ input signals (three stator currents and shaft current) sampled by this card the maximum number of the samples is

$$N_{max} = \frac{f_{smax} T_s}{n_i} = 500.000 \text{ samples} \qquad (5)$$

Due to the operation in the real time and possible choking by the transmission and depositing of the data $N = 400.000$ samples is picked out in the total signal measurements time which gives sampling rate

$$f_s = \frac{N}{T_s} = 40 \text{ kS/s} \qquad (6)$$

for every single input signal.

The power analyzer NORMA-D6000 has the upper boundary sampling rate $f_{smax} = 50$ kS/s independently of the number of the input signals but limited memory storage. The power analyzer has, except of current measurements, registered also the input voltage, speed, power and torque of the motor so that on the occupation of 80 % of the memory capacity the chosen sampling rate is $f_s = 12{,}5$ kS/s, which is 125.000 samples in the 10 sec sampling time.

The reading resolutions of both devices have been satisfying (n = 16 bits) which gives for the voltage inputs into the devices the resolution

$$\Delta u = \frac{u_{max} - u_{min}}{2^n - 1} \qquad (7)$$

By the equation (7) for AD card NI-DAQPad-6015 is $\Delta u = \frac{3-(-3)}{2^{16}-1} = 91{,}55\ \mu\text{V}$ and for power analyzer NORMA-D6000 $\Delta u = \frac{25-(-25)}{2^{16}-1} = 763\ \mu\text{V}$.

In order that by the FFT treatment of the measured signals the possibility of the appearance of the aliasing effect would be neglected the low-pass filter is used. Considering that the lowest sampling rate of the signals was by the power analyzer NORMA-D6000, then definition of Nyquist frequency by equation (1) for the filter frequency 6 kHz would be taken. Blackman window is chosen owing to bigger accuracy, but the problem of the limited memory space by FFT treatment of the signal didn't exist. The chosen sampling rates of both devices have assured 800 samples (NI-DAQPad-6015) and 250 samples (NORMA-D6000) in the period of fundamental harmonic component (50 Hz) that was for the chosen frequency resolution $\Delta f = 0{,}1$ Hz a satisfactory number of samples for the re-construction of signals at the inverse FFT analyze.

4. Analyses of the measurements results

All measurements are executed on four pole squirrel cage induction motor for forklift trucks /8/ with rated data in Δ connection of stator winding:

- voltage 22,5 V
- current 190 A
- power factor 0,76
- frequency 50 Hz
- rotation 1455 min^{-1}
- torque 31,5 Nm.

Shaft currents are measured in delta and star connection at lo-load, at half load and full load. Owing to better differentiation of the frequencies in the fig. 4, 5 and 6 the measurement results are given at the rated point. As to result from item 2 and 3 the time dependence of the shaft currents and frequency specter on fig. 4 and 5 are differentiated only by the convertibility analog into the digital signals - in the AD card NI-DAQPad-6015 and power analyzer NORMA-D6000. For all that the level of the noise at the power analyzer NORMA-D6000 is substantial bigger (approximately 18 dB).

In the table 1 the comparison of the r.m.s. shaft current values for star and delta connection and for AD card NI-DAQ-Pad-6015 and power analyzer NORMA-D6000 is given.

	NI-DAQPad-6015	NORMA-D6000
Y connection	0,495 A	0,920 A
Δ connection	0,705 A	1,073 A

Table 1. R.M.S. values of shat currents in Y and Δ connection of assembled data by AD card NI-DAQPad-6015 and power analyzer NORMA-D6000

With the measurements by the power analyzer NORMA-D6000 86 % bigger current is obtained in comparison with measurements by the card NI-DAQPad-6015 for the star connection and 52 % for delta connection. Mainly (but not completely) these differences can be explained with different measurement errors by equation (7). The measurement results are given on Figure 7 by card NI-DAQPad-6015 and power analyzer NORMA-D6000 in the star con-

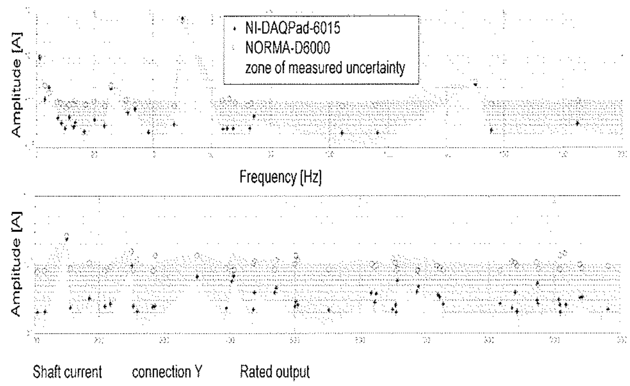

Fig.. 7. Measurements error of power analyzer NORMA-D6000 in comparison with card NI-DAQPad-6015 of important harmonics of shaft current in star connection

nection for important harmonics in the range from 0 to 1000 Hz. The shaded zone is calculated so that with regard to card NI-DAQPad-6015 measured heights (amplitudes) of the current single harmonics are for the plus added errors ($\Delta i_{card} + \Delta i_{NORMA}$), which come out from equation (7) and for the minus errors ($-\Delta i_{card}$). Figure 7 shows that mainly points measured by instrument NORMA-D6000 are within the zone owing to measured uncertainty.

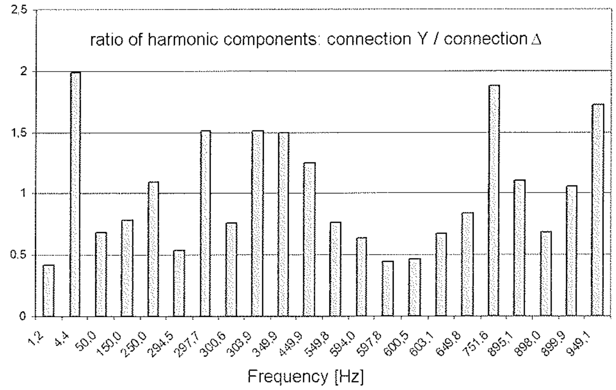

Fig. 8. Ratio of amplitudes important harmonic components of shaft current spectrum: connection Y/connection Δ

Figure 8 shows the ratio of the amplitudes of the important harmonics of the shaft current for star and delta connection. To clear up those results, the comprehensive theoretical analyze is required, which is not subject of this article. Let us remind that theoretically determined mechanism of the beginning single harmonic current component and (theoretically) calculated frequency which differ from the measured frequencies for less then 1 % are stated. Likewise it is determined that in delta connection more different frequencies appeared as in star connection that is confirmed by the measurements.

5. Conclusion

In the article the measurements of shaft currents on (one) low voltage induction motor with electronic equipment are represented. Special care is consecrated to the choice and preparing of the measured equipment and the method of the measurements. Analyses of some results of the measurements and the error of the measurements are done and from this it can be concluded:

- that by relative small size of shaft currents (like in the observed motor) the special attention must be paid to the influence of the leakage field from winding overhang on the size of the measured shaft current (magnetic screen),
- that the equipment for the measurements has to be chosen so, that the quantum noise after equation (7) is as small as possible but the ratio of the voltage with respect to the Rogowski coil current is as big as possible.

6. References

/1/ Seinsch, H. O.; "Lagerstrome bei Drehstrom Induktionsmaschinen, Ursachen und Methoden ihrer Unterdrückung", Conti Elektro-Berichte 15, Jan./Juni 1969., pp. 43-51

/2/ Vujević, Dušan; "Rogowskijev svitak kao strujni tran-sformator", Automatika, Zagreb, 39 (1998), 3-4; str. 125-133

/3/ Ong, R.; Dymond, J.H.; Findlay, R.D.; "Comparison of techniques for measurement of shaft currents in rotating machines", IEEE Transactions on Energy Conversion, Volume 12, Issue 4, Dec. 1997, pp. 363-367

/4/ Štefanko S.; Kurtović I.; Bogut M.; Kovačević M.; Momić M.; "Broken Rotor Bar Detection in Induction Machines Using Measurement of Shaft Currents", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, Grado, Italy, September 13., 2001., pp. 623-626

/5/ Erdman, J. M.; Kerkman, R. J.; Schlegel , D. W.; Skibinski, G. L.; "Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages", IEEE Transactions on Industry Applications, Volume 32., No. 2., March/April 1996, pp. 250-259

/6/ Harris, F.J.; "On the use of windows for harmonic analysis with the discrete Fourier transform", Proceedings of the IEEE, Volume 66, Issue 1, Jan. 1978, pp. 51-83

/7/ Bičanić, K.; Kuzle, I.; Tomiša, T.; "Nekonven-cionalni mjerni pretvarači", Energija, Zagreb, god. 55 (2006), br. 3., str. 328-351

/8/ Baša, K.; Žemva, A.; "Lead-acid Battery state-of-charge estimation for induction motor forklift trucks", Informacije MIDEM 36(2006)1, Ljubljana, str. 37-43

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