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Axial forces of magnetic pull in a disc type induction motor – experimental test.

Streszczenie. *Siły osiowe naciągu magnetycznego występujące w maszynach tarczowych znacząco oddziałują na pracę łożysk, dlatego należy je wziąć pod uwagę na etapie konstrukcji mechanicznej i doboru podzespołów maszyny. Szczególnego znaczenia nabiera to w przypadku, gdy wiadomo, że konstrukcja obwodu magnetycznego nie bilansuje wartości tych sił. W pracy przedstawiono wyniki badań zjawiska naciągu magnetycznego występującego w silniku tarczowym indukcyjnym z jedną szczeliną powietrzną. Zaprezentowano między innymi wyniki pomiarów przebiegów sił osiowych przy biegu jałowym silnika oraz w stanie obciążenia. Główną uwagę poświęcono analizie przebiegów sił osiowych oraz ich zmianom w różnych warunkach pracy silnika.*

Abstract. *Axial forces of magnetic pull occurring in disk type machines significantly affect the operation of bearings, therefore they should be taken into account at the design stage. This is particularly important when it's known that the magnetic circuit doesn't balance the value of these forces. Results of investigation of magnetic pull effect present in disk induction motor with a single air-gap are given in this paper. Among others, results of measurements of axial forces distribution occurring in the motor during idle run and under load conditions are shown. Results of measurements in case of air-gap circumferential asymmetry are also presented. The work is focused on analysis of axial forces' distribution and their changes under different operational conditions of the motor.* ***Siły osiowe naciągu magnetycznego występujące w maszynach tarczowych***

Słowa kluczowe: naciąg magnetyczny, silniki tarczowe, silniki indukcyjne.
Keywords:magnetic pull effect, disk motor, induction motor.

Introduction

This paper presents results of investigation of magnetic pull axial forces in disk induction motor with a single stator and single rotor (abbreviated as AFIM11). Machines with axial flux tend to be more and more widely utilized as generators and motors both [1,2,3]. Their specific properties which are determined by the shape of the magnetic circuit, make them particularly well suited to be used in applications, where one of the main criteria is limited axial length of the machine [4,5]. One of the designs of the magnetic circuit of disk induction motor is a motor with a single air-gap, that is with one stator and one rotor [4,5,6]. Application of such motor design is justified above all in low power motors, where for economical reasons there is no need of using popular designs with double stator and double rotor [5]. However, a significant drawback of this solution is found in high values of magnetic pull axial forces acting between stator and rotor and present during normal operation of the machine [4,5,6,7]. These forces bear a considerable impact on the bearings' operation, therefore they must be taken into account in the process of mechanical design and selection of machine components [4,5,6]. Numerous publications may be found on measurements and analyses of radial magnetic pull in cylindrical motors. Results of such works are presented, among others, by Dorrell et al. [8,9] and Tenhunen et al. [10]. However, there are no publications on issue of axial magnetic pull in disk motors, even though this pull's impact on disk motor operation is quite significant.

Results of experimental investigation of magnetic pull axial forces in induction disk motor are presented in the current paper (model of this motor is shown in Fig.1). Measurements were conducted at dedicated test stand equipped with EMS70-5kN strain gauges (Fig.3). The main aim of this work was to determine the values of magnetic pull axial forces and their variations in different operational modes of the motor, to identify dominant frequencies in the waveforms of those forces and to find out the impact of magnetic pull on the bearing, which is the most sensitive and susceptible to failures component of the motor.

Model of disk induction motor

The object of the investigation was a model induction disk motor, number of poles 2p=6, with single stator and single rotor (AFIM11). The basic data on dimensions of magnetic circuit, winding and rated parameters of the tested motor is given in Table 1; model of the magnetic circuit is shown in Fig.2. The stator and rotor cores are wound of generator strip, type M470-50A. Slots were cut into the cores with the help of spark erosion method. Symmetrical, three-phase winding with winding factor kw=0.933 is placed in the stator slots. The rotor contains squirrel cage winding with two short-circuiting end rings (upper and lower).

Table 1. Basic design data of model motor AFIM11

Parameter			
Outer diameter - stator and rotor	Dz	[mm]	205
Inner diameter - stator and rotor	Dw	[mm]	130
Length of motor's magnetic circuit	L	[mm]	100
Air-gap length	δ	[mm]	0.85
Number of poles	2p	-	6
Number of stator phases	m	-	3
Number of stator slots	Qs	-	36
Number of rotor slots	Qw	-	40
Swindi tator's ng factor	kw	-	0.933
Rated voltage	ULL	[V]	400
Rated frequency	fs	[Hz]	50
Rated power	Pn	[W]	1500
Rated torque	Tn	[Nm]	15
Rated current	In	[A]	3.4

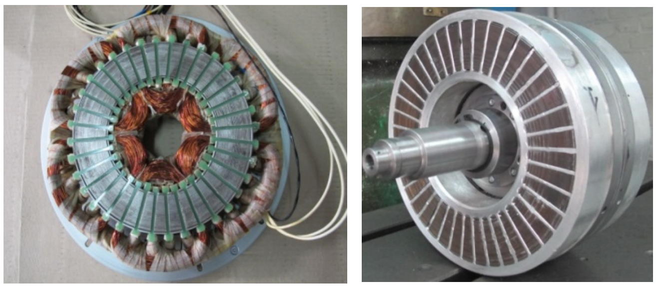


Fig.1. Model of the motor:
a) Stator with winding, b) Rotor fitted with bearing into the shaft.

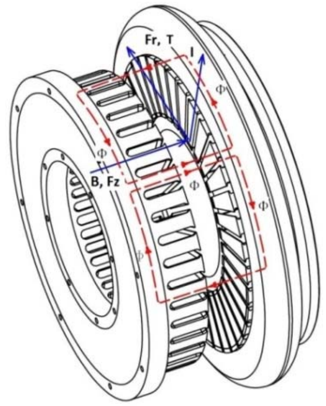


Fig.2. Model of the magnetic circuit of tested motor, vectors' directions: flux density B, phase current I, electromagnetic torque T, circumferential force Fr, axial force Fz and flow direction of main magnetic flux Φ

The motor model shown in Fig.1 has been installed at the dedicated test stand, which has been adapted to the measurements of magnetic pull axial forces (Fig.3). The stand is equipped with four EMS70-5kN strain gauges, located in the front panel. The stator with winding is also fixed to this panel. The placement and numbering of different sensors is shown in Fig.3b.

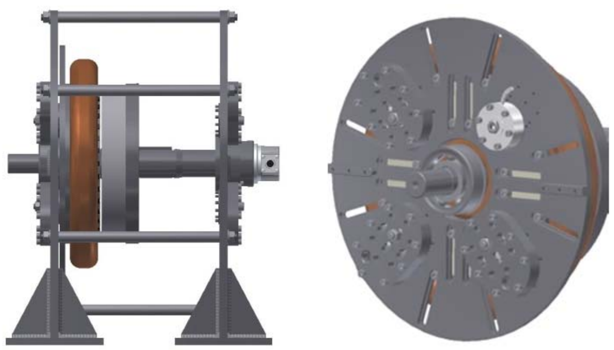


Fig.3. a) Model of the test stand, b) Placement of EMS70-5kN sensors - front panel of the test stand.

Magnetic pull forces during idle run

The measurements of magnetic pull axial forces versus supply voltage and at constant supply frequency were done while the motor was running idle. The tests were done for motor with uniform air-gap, air-gap length was 0.85mm. The dependence of the resultant axial force of magnetic pull on relative value of the main magnetic flux is shown in Fig.4. Change of motor's supply voltage (while the supply frequency is maintained constant), brings about a change in main magnetic flux Φ (this has been referenced to the nominal flux value Φ_n in the chart).

The curve shown in Fig.4 may be approximated with a polynomial of the 4th order. In such case, the dependence of the magnetic pull force on the relative value of main magnetic flux for the tested motor may be expressed as:

Attention must be drawn to actual values of measured magnetic pull axial forces corresponding to the rated (nominal) value of motor's main magnetic flux. This value is equal to c. 1650 N and it is about 9 times greater than the value of circumferential force Fr, which generates rated rotational torque (this force measured at the average radii of stator and rotor disks of the model motor is equal to c. 180 N). Methods of limiting such large axial forces are known [4,5,6]; however, in case of relatively low-power motors they will unduly complicate machine's design and increase its manufacturing costs. A cheaper solution to apply at the design stage is to strengthen the bearing units of disk machines, which will facilitate the transmission of axial forces of such order.

$$F_z = -1493 \cdot \left(\frac{\Phi}{\Phi_n}\right)^4 + 4121 \cdot \left(\frac{\Phi}{\Phi_n}\right)^3 - 2225 \cdot \left(\frac{\Phi}{\Phi_n}\right)^2 + 1331 \cdot \left(\frac{\Phi}{\Phi_n}\right) - 65 \quad (1)$$

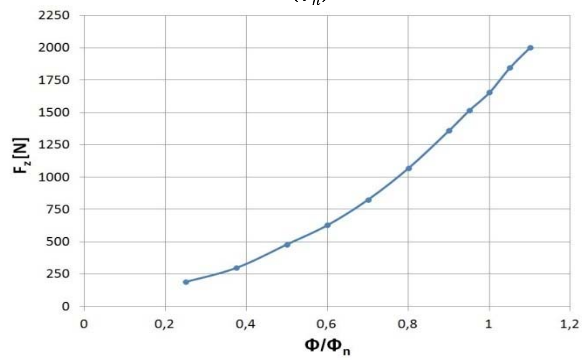
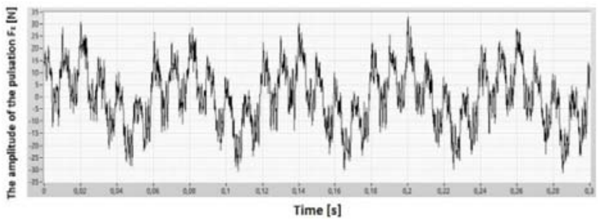


Fig.4. Dependence of axial magnetic pull force on main magnetic flux.



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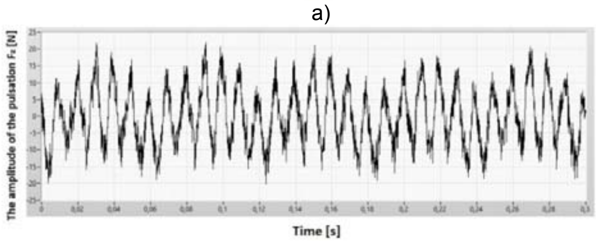

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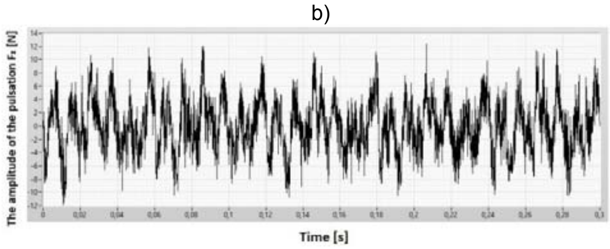

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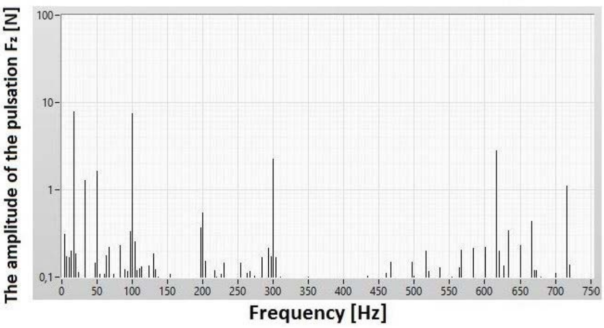
Fig.5. Waveforms of variable component of axial magnetic pull force, when main magnetic flux is varied:
a) - supply 400V,50Hz, Φ/Φ_n=1; b) - supply 240V,50Hz; Φ/Φ_n=0.6; c) - supply 100V,50Hz, Φ/Φ_n=0.2

The time courses (waveforms) of the axial force were recorded for different values of the supply voltage (corresponding to the relative values of the main magnetic flux - see Fig.4). Harmonic analysis of these waveforms was conducted. The results are shown in Table 2 and Fig.5. Table 2 shows only the selected harmonics, i.e. those with dominant amplitude values. These are harmonics related to: rotational frequency of the magnetic field (16.67 Hz) and its multiplicities and slot frequencies determined by the rotor's rotational frequency and change of reluctance of the magnetic circuit due to the presence of stator and rotor slots. The constant component was removed from the waveforms shown in Fig.5 for the sake of clarity. Thus, the waveforms present directly the value of magnetic axial force pulsation.

Table 2. Amplitudes of pulsation of axial force Fz for selected harmonic frequencies when main magnetic flux is varied and supply voltage frequency is constant (f=50Hz); motor running idle.

	Frequency of the pulsation F_z [Hz]							
	16.67	**33.33**	**50**	**100**	**300**	**616.67**	**666.67**	**716.67**
Amplitude of the pulsation F_z [N] Φ/Φ_n =1	7.76	1.27	1.65	7.53	2.26	2.8	0.39	1.11
Amplitude of the pulsation F_z[N] Φ/Φ_n =0.8	5.62	1.08	1.26	9.47	0.3	1.75	0.17	0.59
Amplitude of the pulsation F_z[N] Φ/Φ_n =0.6	2.64	0.91	0.64	7.34	0.29	1.04	0.13	0.41
Amplitude of the pulsation F_z[N] Φ/Φ_n =0.4	0.76	1.3	0.23	5.24	0.12	0.53	0.07	0.21
Amplitude of the pulsation F_z[N] Φ/Φ_n =0.2	0.31	1.18	0.5	2.29	0.1	0.21	0.03	0.1



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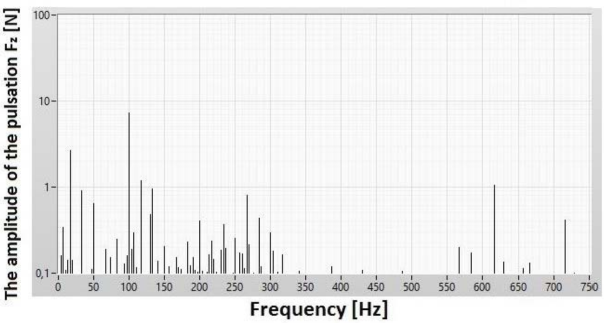

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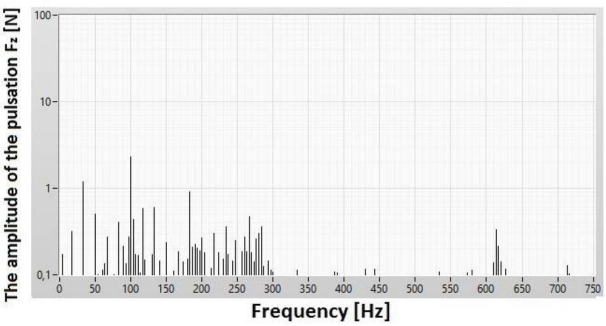
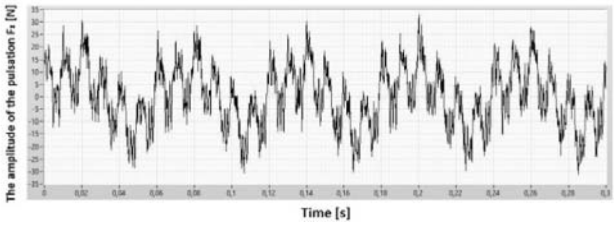


c)

Fig.6. Harmonic analysis of variable component of axial magnetic pull force, when main magnetic flux is varied:
a) - supply 400V,50Hz, Φ/Φ_n=1; b) - supply 240V,50Hz; Φ/Φ_n=0.6; c) - supply 100V,50Hz, Φ/Φ_n=0.2

The recorded waveforms as well as their harmonic analysis show that dominant frequencies in the axial force course are:
- the frequency of magnetic field rotation (16.67 Hz), which corresponds to synchronous speed of 1000 rpm,
- doubled supply frequency (100 Hz), which has been accurately explained by Dorrel et al. [9],
- supply voltage frequency (50 Hz),
- doubled frequency (33.33 Hz) of magnetic field rotation,
- characteristic frequencies 600-750 Hz related to change of magnetic circuit reluctance at a current rotor's rotational speed.



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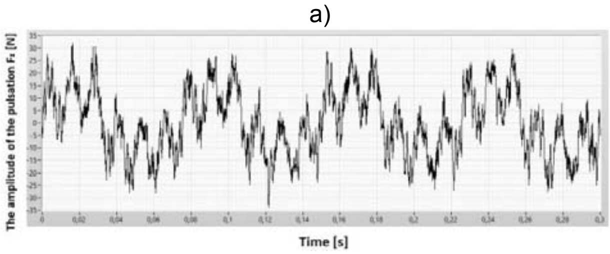

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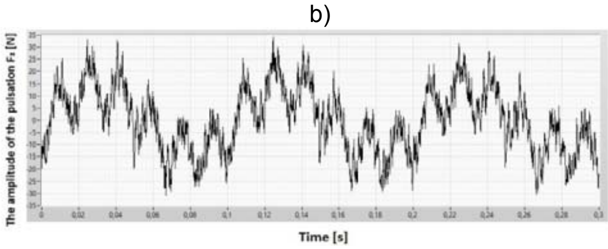
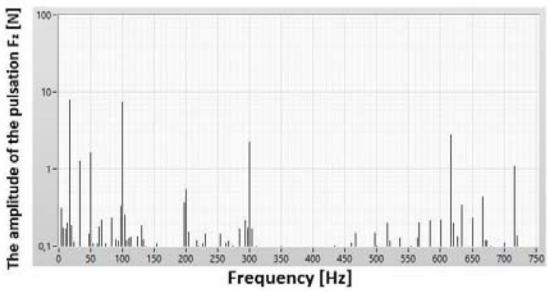


c)

Fig.7. The waveforms of variable components of axial magnetic pull force, with varied supply voltage frequency and constant main magnetic flux:
a) - 400V,50Hz supply, Φ/Φ_n=1; b) - 320V,40Hz supply, Φ/Φ_n=1; c) - 240V,30Hz supply, Φ/Φ_n=1;

As the main magnetic flux decreases, the amplitude of 16.67 Hz harmonic changes in accordance with the square of main magnetic flux. The effect is similar in case of frequencies related to variable reluctances of the stator and rotor magnetic cores. These are frequencies ranging from 600 to 716.67 Hz. Their amplitudes change in accordance with square of main magnetic flux. We must also note 100 Hz frequency, i.e. double of the supply voltage frequency fs=50 Hz. The amplitude of the axial force at this frequency is dominant in almost all recorded waveforms when magnetic flux was changing and this is due to interaction of magnetic flux density and phase current [9].

The measurements of axial magnetic pull forces were also conducted for idle run conditions, with variable supply frequency and main magnetic flux kept constant, i.e. in accordance with the principle of U/f=const. The dependence of resultant axial magnetic pull force on these changes is shown in Fig.9.



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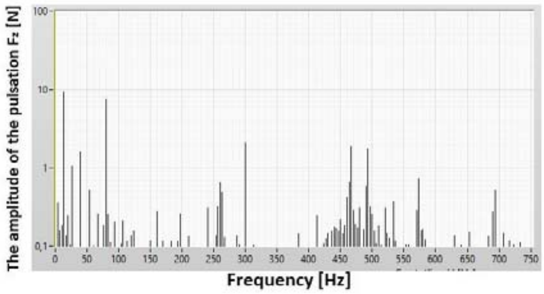

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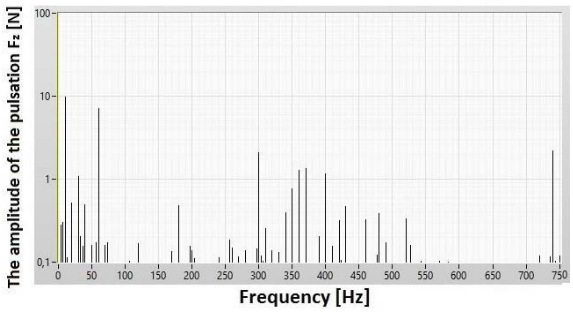


c)

Fig.8. The harmonic analysis of variable components of axial magnetic pull force, with varied supply voltage frequency and constant main magnetic flux:
a) - 400V,50Hz supply, Φ/Φ_n=1; b) - 320V,40Hz supply, Φ/Φ_n=1;
c) - 240V,30Hz supply, Φ/Φ_n=1;

The waveforms of magnetic pull axial forces were also recorded for this type of supply and their harmonic analysis was also conducted. Same as in previous case the constant component was removed from the waveforms for the sake of clarity. The results of recorded axial force waveforms, at U/f=const, for frequencies ranging from 10 to 50 Hz, are presented in Table 3 and in Fig.7 and Fig.8.

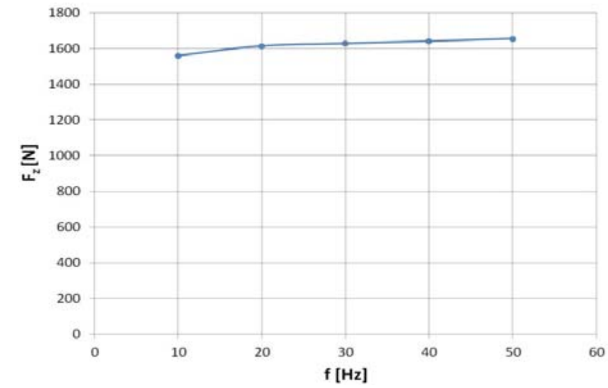


Fig.9. Axial magnetic pull force vs. supply frequency, main magnetic flux was kept constant.

It may be stated, looking at the waveform shown in Fig.9, that the value of magnetic pull forces is independent of supply voltage frequency when the main magnetic flux is constant. In reality, the axial force varies (it may be observed in the presented graph), but the changes are so small in relation to the initial value that the waveform may be assumed to be constant.

Results shown in Fig.7,8 and Table 3 show that when supply voltage frequency is varied and main magnetic flux is kept constant, dominant frequencies in the waveforms of the magnetic pull axial forces are similar to the results presented in Table 2 and Fig.5,6. We may observe that for each frequency of the supply voltage, the dominant component in the axial force pulsation waveform is the one related to the rotational speed of the magnetic field.

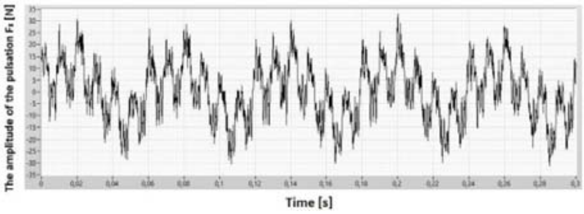
Table 3. Amplitudes of axial force pulsation Fz for selected harmonics with varied supply voltage frequency and U/f=const; motor's idle run.

		Harmonic number							
		1	2	3	6	18	37	40	43
400 V	Frequency of the pulsation F_z [Hz]	16,67	33,33	50	100	300	616,67	666,67	716,67
50 Hz	Amplitude of the pulsation F_z [N]	7,76	1,27	1,65	7,53	2,26	2,8	0,39	1,11
320 V	Frequency of the pulsation F_z [Hz]	13,33	26,67	40	80	240	493,33	533,33	573,33
40 Hz	Amplitude of the pulsation F_z[N]	9,23	1,06	1,57	7,51	0,3	1,77	0,37	0,72
240 V	Frequency of the pulsation F_z [Hz]	10	20	30	60	180	370	400	430
30 Hz	Amplitude of the pulsation F_z[N]	9,78	0,51	1,07	7,18	0,48	1,33	1,14	0,47
160 V	Frequency of the pulsation F_z [Hz]	6,66	13,33	20	40	120	246,66	266,66	286,66
20 Hz	Amplitude of the pulsation F_z[N]	9,61	0,22	1,24	6,72	0,68	1,94	2,34	0,27
80 V	Frequency of the pulsation F_z [Hz]	3,33	6,66	10	20	60	123,33	133,33	143,33
10 Hz	Amplitude of the pulsation F_z[N]	11,34	0,49	0,88	4,37	0,67	0,27	1,29	0,1

When supply frequency is 50 Hz, the magnetic field rotational speed is 1000 rpm, so the dominant component is of 16.67 Hz frequency. Analogically, in case of supply frequency equal to 30 and 40 Hz, the dominant components are present at 13.33Hz and 10 Hz, respectively. The values of component amplitudes for these frequencies may be considered close and independent of the supply frequency value. The second dominant component in the axial forces' waveforms is the component of double the supply frequency 2fs. The amplitude values of this component may also be admitted to be independent of the supply voltage frequency (differences may be observed only when the supply voltage and frequency are very low).

Frequencies related to the change of reluctance of the magnetic circuit and rotor's rotational speed may be distinguished also from results shown in Fig.8. These are frequencies of 35th to 43th harmonics.

Attention must also be paid to 300 Hz component; in all cases shown in Fig.8 this is constant. Since in this case the frequency of supply voltage was varied (and, subsequently, rotor's rotational speed also changed), we must acknowledge that this component is not related to the multiplicity of the supply frequency or of magnetic field rotational speed. When changes of 300 Hz component (see Fig.6) are compared, then it may be stated that this component depends solely on the value of main magnetic flux; when this flux changes a little (in relation to its nominal value - Φ/Φ_n =0.8), the component significantly decreases.



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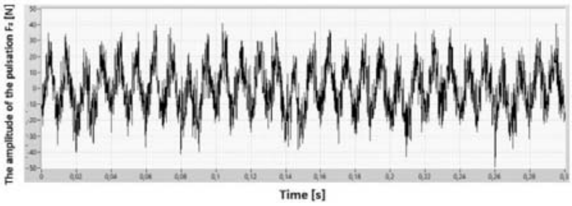

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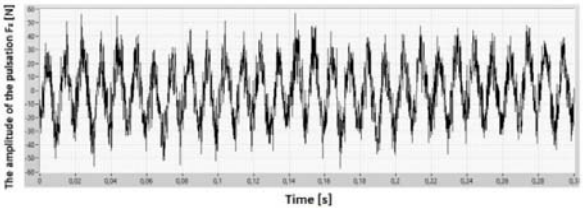

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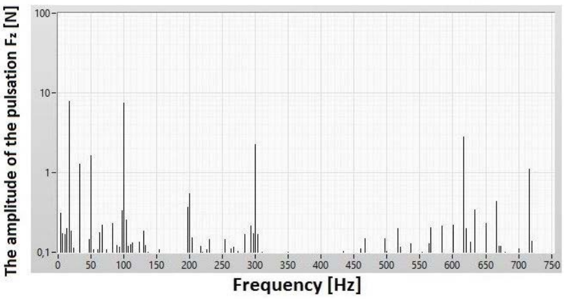
Fig.10. The waveforms of the variable component of the magnetic pull axial forces. Supply was rated at 400V, 50Hz, load torque was varied: a) - idle run; b) - load torque 10 Nm; c) - load torque 20 Nm;



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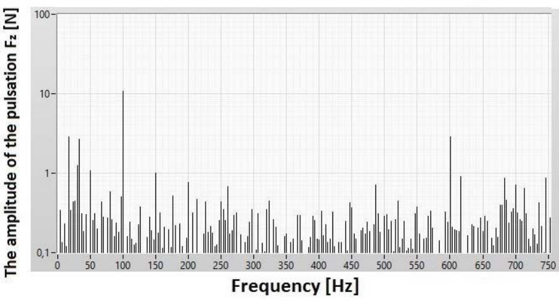

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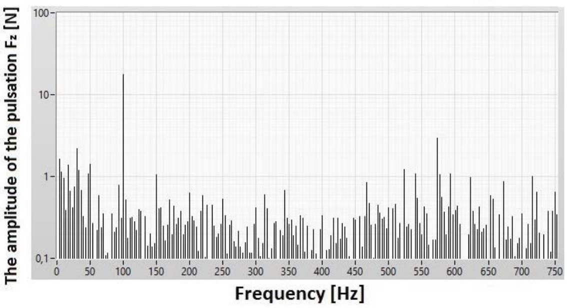

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Fig.11. Harmonic analysis of the variable component of the magnetic pull axial forces. Supply was rated at 400V, 50Hz, load torque was varied: a) - idle run; b) - load torque 10 Nm; c) - load torque 20 Nm;

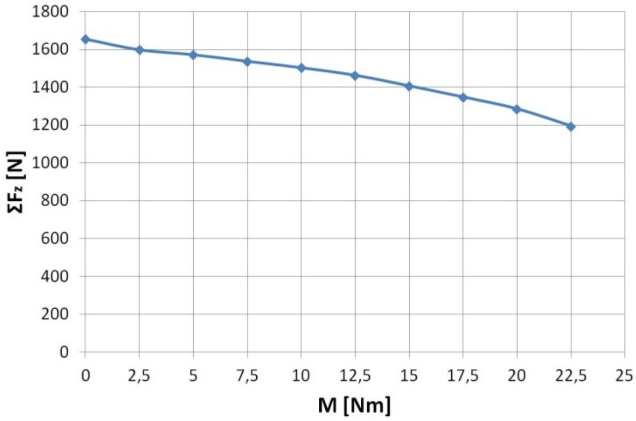

Fig.12. Magnetic pull axial force vs. motor's load torque

Magnetic pull forces at varying loads

The waveforms and values of magnetic pull axial forces were recorded also for symmetrical air-gap and loaded motor. Motor was loaded with torque ranging from nil (idle run) to 22.5 Nm, which was equal to 150% of the rated torque. The results (recorded waveforms with constant component removed) are shown in Fig. 10 and Fig.11. The amplitudes of different dominant harmonics are set out in Table 4.

After analyzing the presented data we may deduce that change of load torque of induction disk motor causes the following changes in the axial force pulsation waveforms:

- decrease of the 16.67 Hz harmonic amplitude (this is harmonic due to field rotation frequency),
- increase of 100 Hz harmonic amplitude (this is frequency equal to double the supply frequency - 2fs,)
- shift of component harmonics resulting from changes in reluctance of the magnetic circuit and current rotor's rotational speed towards lower frequencies (this is analogous to the effect of decrease in rotor speed, while the load increases). For motor's idle run the dominant reluctance frequency was 616.67 Hz with amplitude 2.8 N; at load torque equal to 20 Nm the dominant frequency was 573.33 Hz and the harmonic amplitude was 2.9 N (see Fig. 11 a,c).

Moreover, the increase in load torque causes a decrease in overall average value of magnetic pull forces; this is shown in

Conclusion

Results of investigating the effect of magnetic pull in disk-type induction motor with single air-gap are given in the paper. The presented results make it possible to determine the value of magnetic pull axial force under different operational conditions and its variations when supply parameters or load are changed. Waveforms of axial force pulsation and their harmonic analyzes are presented for each discussed operational condition. Different characteristic frequency components have been determined as well as their variations due to changes in the input quantities.

The presented data should be used in the design of bearing units in disk-type machines. Improper calculation of axial forces' values may cause decrease in overall machine efficiency as well as premature wear of bearings due to their unsuitable selection. This originates from harmful friction effects and excess mechanical losses. These forces must be taken into account while calculating equivalent bearing loads.

Table 4. Amplitudes of axial force Fz pulsation for selected harmonic frequencies and average value of axial force ΣFz; supply was rated at 400 V, 50 Hz; load torque was varied.

Frequency of the pulsation F_z [Hz]	**16.67**	**33.33**	**50**	**100**	**300**	**616.67**	**666.67**	**716.67**	**ΣF_z [N]**
Idle run	7.76	1.27	1.65	7.53	2.26	2.80	0.39	1.11	1656
2.5 Nm	5.89	2.02	1.30	8.26	0.24	0.62	0.25	0.19	1599
5 Nm	3.61	1.77	1.28	8.40	0.24	0.28	0.31	0.11	1573
7.5 Nm	3.63	2.33	2.58	9.47	0.46	0.52	0.10	0.05	1538
10 Nm	2.83	2.69	1.07	10.76	0.09	0.90	0.12	0.31	1504
12.5 Nm	2.01	2.47	0.43	11.59	0.30	0.68	0.06	0.29	1464
15 Nm	1.91	2.44	1.12	13.68	0.01	0.21	0.06	0.27	1408
17.5 Nm	1.78	1.81	0.38	15.16	0.08	0.04	0.19	0.34	1349
20 Nm	1.38	1.18	1.41	17.35	0.41	0.06	0.34	0.99	1286
22.5 Nm	1.34	0.60	3.2	20.18	0.13	0.26	0.28	0.14	1195

The relationship between bearings' durability and their loads is of exponential character. If axial forces were disregarded, then bearings' lifetime would decrease by at least 3.33s- times in relation to predicted value, where s is the ratio of the equivalent load to radial load. For these machines ball bearings or cone bearings are recommended.

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