Analysis of magnetic pull effect in disk induction motor with symmetrical/asymmetrical air-gap

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Abstract. Disk induction motor presents an interesting alternative to standard machine on account of its limited axial dimension. Its application may be contemplated for mine industry machines. However, in case of the design presented in this paper, a most significant drawback lies in magnetic pull axial forces appearing during normal operation of the machine and affecting bearing performance. This is why such forces should be considered at the design stage; this is particularly true, when design of magnetic circuit does not counterbalance those forces. The issue of magnetic pull occurring in disk induction motor with a single air-gap is presented in the paper for both symmetrical and asymmetrical air-gap. Results of calculations and measurements of axial forces under differing operating conditions of the motor are demonstrated. Particular attention is paid to analysis of axial force waveforms and their variations for different motor operating conditions.

1. Introduction

Disk induction motors operate on the identical principle as standard cylindrical induction motors. The difference lies in the shape of magnetic circuit. In case of disk machines, axial dimension is limited at the expense of increased diameter. Such motors are therefore well adapted to applications, where one of main criteria is limitation of axial length of the machine [1, 2]. Examples of such applications may be found also in broadly defined mine industry.

Among designs of disk induction machines, we may distinguish a motor with a single air-gap, that is one stator and one rotor [1, 2, 3]. This design is justified in case of low power motors, where it is not necessary (and not acceptable from economical point of view) to use popular designs with double stator and double rotor [2]. A significant drawback of this design is that high magnetic pull axial forces (occurring between stator and rotor) emerge during normal operation of the machine [1, 2, 3, 4]. These forces substantially affect bearing performance and therefore should be taken into account during design of mechanical construction and selection of machine subassemblies [1, 2, 3]. Numerous publications on measurements and computational analyses of radial magnetic pull in cylindrical machines are known. Results of such research have been presented by Dorrell et al. [5,6], Tenhunen et al. [7] and others. However, there is a notable absence of publications dedicated to axial magnetic pull issue in disk motors, even though impact of this pull on machine operation is significant.

Results of calculations and experimental tests of magnetic pull axial forces are given in this paper. Investigation has been devoted to disk induction motor, its model in shown in Figure 1 and Figure 2.
The tests have been conducted at a dedicated test bench equipped with strain gauges EMS70-5kN. The main goal of the work was to determine values of magnetic pull axial forces present in the motor and their variations in selected motor operating conditions, to evaluate dominant frequencies in time courses of the axial forces and to determine the impact of magnetic pull on motor’s structural elements.

2. Model of disk induction motor

During the research, we have investigated model disk induction motor AFIM11, with single stator and single rotor, number of pole pairs 2p=6. The basic data on geometric dimensions of magnetic circuit, winding and rated parameters of the discussed motor are shown in Table 1; the physical model of electromagnetic circuit elements is shown in Figures 1 and 2. The stator/rotor cores of model motor are made of a generator strip roll M470-50A, with slots cut out by electro-erosion (spark erosion) method. The stator slots are packed with symmetrical three-phase winding with winding factor equal to kw=0.933. Rotor’s cage winding is fitted with two end-rings (upper and lower).

**Figure 1.** Stator with winding.  
**Figure 2.** Rotor fitted with bearing into the shaft.

**Table 1.** Basic design data of model motor AFIM11.

| Parameter                              | Value  |
|----------------------------------------|--------|
| 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  |
| Stator's winding 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  |

Motor model shown in Figures 1 and 2 has been installed at a dedicated test bench, which had been adapted for measurements of axial forces of magnetic pull (Figure 3). The bench is equipped with four
strain gauges EMS70-5kN, located in the front panel; the stator together with its winding has also been secured to this panel. Placement and numbering of different sensors are shown in Figure 4.

![Figure 3. Model of the test stand.](image)

![Figure 4. Placement of EMS70-5kN sensors - front panel of the test stand.](image)

3. Magnetic pull forces during idle run

First of all, tests of motor with symmetrical air-gap equal to 0.85 mm (along the entire circumference) have been conducted. With motor running idle, the measurements of axial forces of magnetic pull versus supply voltage at constant frequency have been managed. The curve illustrating the dependence of resultant axial force of magnetic pull against the relative value of main magnetic flux is shown in Figure 5. Change of supply voltage at constant frequency produced changes in main magnetic flux $\Phi$; in Figure 5 this flux has been related to the rated magnetic flux value $\Phi_r$ (at rated supply).

![Figure 5. Dependence of axial magnetic pull force on main magnetic flux.](image)

Attention must be drawn to measured value of magnetic pull axial forces for the rated value of main magnetic flux, this was measured at $c. 1650$ N. This is about 9 times greater than value of circumferential force $F_r$, which generates rotational torque; this force measured at averaged radii of stator/rotor disks is equal to $c. 180$ N. Methods for limiting such high axial forces are known [1, 2, 3];
however, in case of relatively low power motors their application would greatly increase the complexity of motor design and raise production costs. A cheaper solution of this problem is to strengthen the bearing assembly of disk machines so that such high axial forces could be withstood. This strengthening should be accomplished at the design stage.

For different values of supply voltage, corresponding to relative values of main magnetic flux as in Figure 5, the waveforms of axial force have been recorded and harmonic analysis has been conducted. The results are shown in Table 2 and Figure 6.

Harmonics with dominant amplitudes only are shown in Table 2. These are harmonics related to: magnetic field’s rotational frequency (16.67 Hz) and its multiplicities and slot frequencies determined by rotor’s rotational frequency and change in reluctance of magnetic circuit due to the presence of stator/rotor slots. The constant component has been removed for the sake of transparency from waveforms shown in Figure 6. The presented waveforms illustrate directly the pulsation value of magnetic pull axial force.

The recorded waveforms as well as the harmonic analysis show that predominant frequencies in the axial force waveforms are:

- magnetic field’s rotational frequency (16.67 Hz), corresponding to synchronous speed of 1000 rpm,
- doubled frequency (100 Hz) of supply voltage; this has been explained thoroughly by Dorrel et al. [6],
- supply voltage frequency (50 Hz),
- doubled frequency (33.33 Hz) of magnetic field’s rotation,
- characteristic frequencies 600-750 Hz due to changes in reluctance of magnetic circuit at a current rotor rotational speed.

As the main magnetic flux decreases, the amplitude of 16.67 Hz harmonic changes proportionately to change in main magnetic flux squared. In case of frequencies related to variable reluctance of stator/rotor magnetic core similar effect is observed; these are frequencies in the range 600-716.67 Hz. Their amplitudes change in proportion to change in main magnetic flux squared. We must also note the frequency 100 Hz (this is double of supply frequency fs=50 Hz). Amplitude of axial force at this frequency is nearly always dominant in all recorded waveforms, with variations in main magnetic flux. This is due to the mutual action of magnetic flux density and phase current [6].

| Frequency of the pulsation Fz [Hz] | 16.67 | 33.33 | 50 | 100 | 300 | 616.67 | 666.67 | 716.67 |
|-----------------------------------|-------|-------|----|-----|-----|--------|--------|--------|
| Amplitude of the pulsation Fz [N] |       |       |    |     |     |        |        |        |
| \( \Phi/\Phi_n =1 \)              | 7.76  | 1.27  | 1.65| 7.53| 2.26| 2.8    | 0.39   | 1.11   |
| Amplitude of the pulsation Fz [N] |       |       |    |     |     |        |        |        |
| \( \Phi/\Phi_n =0.8 \)             | 5.62  | 1.08  | 1.26| 9.47| 0.3  | 1.75   | 0.17   | 0.59   |
| Amplitude of the pulsation Fz [N] |       |       |    |     |     |        |        |        |
| \( \Phi/\Phi_n =0.6 \)             | 2.64  | 0.91  | 0.64| 7.34| 0.29| 1.04   | 0.13   | 0.41   |
| Amplitude of the pulsation Fz [N] |       |       |    |     |     |        |        |        |
| \( \Phi/\Phi_n =0.4 \)             | 0.76  | 1.3   | 0.23| 5.24| 0.12| 0.53   | 0.07   | 0.21   |
| Amplitude of the pulsation Fz [N] |       |       |    |     |     |        |        |        |
| \( \Phi/\Phi_n =0.2 \)             | 0.31  | 1.18  | 0.5 | 2.29| 0.1  | 0.21   | 0.03   | 0.1    |
Figure 6. Waveforms and harmonic analysis of variable component of magnetic pull axial force; main magnetic flux is varied: a, b) supply 400V, 50Hz, $\Phi/\Phi_n=1$; c, d) supply 240V, 50Hz; $\Phi/\Phi_n=0.6$; e, f) supply 100V, 50Hz, $\Phi/\Phi_n=0.2$.

4. Magnetic pull forces at varying load

The waveforms and values of magnetic pull axial force have also been recorded with loaded motor and symmetrical air-gap. Motor was loaded with torque varying from zero (idle run) up to 22.5 Nm (this corresponds to 1.5 times rated load torque). The waveforms with constant component removed are shown in Figure 7. Amplitudes of different dominant harmonic frequencies are set out in Table 3.

When these data are analysed, we may conclude that change in load torque of induction disk motor leads to following effects in axial force pulsation waveforms:

- decrease in amplitude value of 16.67 Hz harmonic (which is due to magnetic field’s rotational speed),
- increase in amplitude value of 100 Hz harmonic (this is 2fs frequency),
- shift of harmonic components (due to changes in reluctance of magnetic circuit and current rotor’s rotational speed) towards lower frequencies (this is similar to decrease of rotor’s speed corresponding to increased load). In case of motor’s idle run the dominant reluctance frequency was 616.67 Hz, amplitude 2.8 N, while for load torque 20 Nm the dominant frequency was 573.33 Hz amplitude 2.9 N (Figure 7 b, f).

Moreover, increase of motor load leads to decrease of total average value of magnetic pull forces. This is shown in Figure 8.
Table 3. Pulsation amplitudes of axial force $F_z$ for selected harmonic frequencies and average value of axial force $\Sigma F_z$ at rated supply 400V, 50 Hz; varied motor load torque.

| Frequency of the pulsation $F_z$ [Hz] | 16.67 | 33.33 | 50 | 100 | 300 | 616.67 | 666.67 | 716.67 | $\Sigma F_z$ [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          |

*Figure 7. Waveforms and harmonic analysis of variable component of magnetic pull axial force; rated supply 400V, 50 Hz, load is varied: a, b) idle run, c, d) load torque 10 Nm, e, f) load torque 20 Nm.*
5. Impact of air-gap asymmetry on magnetic pull forces

The problem of maintaining symmetry of the air-gap and circumferential symmetry in particular often arises in disk motors (Figure 9). This is caused by relatively large external diameters of rotor disks in relation to their thickness [1, 2]. If rotor design is faulty, then rotor may be whippy and its rigidity may be low. This asymmetry may also result from tolerance chain of different subassemblies. The length of the air-gap $\delta$ with circumferential asymmetry as shown in Figure 9 is described by relationship (1).

This is a function of current disk radii $r$ (where we analyse the air-gap), angle $\beta$ and angle $\alpha$ measured along the circumference of $r$ radius.

$$\delta(r, \alpha, \beta) = \delta_0 + r \cdot \sin(\beta) \cos(\alpha)$$

where:

- $r$ – current disk radius,
- $\alpha$ – current angle measured along the circumference of $r$ radius, and:
- $\beta$ – angle of air-gap non-uniformity (disk angle of inclination)
- $\delta_0$ – rated air-gap (under symmetrical conditions); with asymmetry this is an air-gap in shaft axis.

The dedicated test bench displayed in Figure 3 makes it possible to introduce circumferential asymmetries of the disk motor’s air-gap. Therefore, impact of circumferential asymmetry of the air-gap on values and waveforms of magnetic pull axial forces in a model motor has been investigated. The tests have been run for two cases of circumferential asymmetry of the air-gap:

1. asymmetry $\Delta = 0.5$ mm, where $\delta_0 = 0.85$ mm, $\delta_{\text{min}} = 0.5$ mm, $\delta_{\text{max}} = 1.0$ mm
2. asymmetry $\Delta = 1.0$ mm, where $\delta_0 = 0.85$ mm, $\delta_{\text{min}} = 0.3$ mm, $\delta_{\text{max}} = 1.3$ mm.

The elaborated results are shown in Tables 4, 5 and Figure 10.
Results of measurements of average values of axial forces with different strain gauges (cf. Figure 4) are presented in Table 4. These results demonstrate the direction (geometrical) of evolving asymmetry; location of different strain gauges shown in Figure 4 is taken into account. When asymmetry is changed, values of forces measured by sensors F1 and F4 decrease, while those measured by sensors F2 and F3 increase; this testifies unequivocally to the direction of disk inclination. Appropriate placement of strain gauges may therefore constitute the basis for diagnosing air-gap uniformity in disk motors. As the air-gap asymmetry increases (disk inclination angle is greater), the total value of axial force $\Sigma F_z$ defined by relationship (2) increases. However, these changes are not significant and are equal to c. 5%.

$$\Sigma F_z = F1 + F2 + F3 + F4$$

(2)

**Table 4.** Average values of axial forces versus changes in circumferential symmetry of the air-gap; forces recorded with strain gauges F1-F4 at rated supply 400V, 50Hz, motor running idle.

| Circumferential symmetry of air-gap | F1 [N] | F2 [N] | F3 [N] | F4 [N] | $\Sigma F_z$ [N] |
|------------------------------------|--------|--------|--------|--------|-----------------|
| Symmetrical air-gap                | 417    | 416    | 379    | 444    | 1656            |
| Circumferential asymmetry $\Delta=0.5$ mm | 347    | 468    | 461    | 394    | 1671            |
| Circumferential asymmetry $\Delta=1.0$ mm | 308    | 519    | 529    | 383    | 1741            |

Comparison of waveforms and different harmonics of axial forces under conditions of symmetry and asymmetry of the air-gap is shown in Table 5 and Figure 10.

**Table 5.** Pulsation amplitudes of axial force $F_z$ for selected harmonic frequencies versus changes in circumferential asymmetry of the air-gap; main magnetic flux is varied, supply frequency is constant $f=50$Hz, motor running idle.

| Frequency of the pulsation $F_z$ [Hz] | 16.67 | 33.33 | 50 | 100 | 300 | 616.67 | 666.67 | 716.67 |
|--------------------------------------|-------|-------|----|-----|-----|--------|--------|--------|
| 400V, 50 Hz                          |       |       |    |     |     |        |        |        |
| Symmetrical air-gap                  | 7.76  | 1.27  | 1.65 | 7.53 | 2.26 | 2.80   | 0.39   | 1.11   |
| Asymmetrical air-gap $\Delta=0.5$ mm | 26.07 | 1.25  | 1.61 | 9.64 | 0.52 | 2.47   | 0.41   | 0.76   |
| Asymmetrical air-gap $\Delta=1.0$ mm | 56.05 | 2.04  | 1.55 | 9.49 | 0.15 | 2.81   | 0.71   | 1.3    |

**Figure 9.** Circumferential asymmetry of the air-gap.
| Voltage | Type | Δ | amplitude | phase | waveform | frequency | waveform |
|---------|------|---|-----------|-------|----------|-----------|----------|
| 320V, 50Hz | Symmetrical air-gap | | | | | | |
| | | | | | | | |
| 320V, 50Hz | Asymmetrical air-gap Δ=0.5 mm | | | | | | |
| | | | | | | | |
| 320V, 50Hz | Asymmetrical air-gap Δ=1.0 mm | | | | | | |
| | | | | | | | |
| 240V, 50Hz | Symmetrical air-gap | | | | | | |
| | | | | | | | |
| 240V, 50Hz | Asymmetrical air-gap Δ=0.5 mm | | | | | | |
| | | | | | | | |
| 240V, 50Hz | Asymmetrical air-gap Δ=1.0 mm | | | | | | |
| | | | | | | | |
| 160V, 50Hz | Symmetrical air-gap | | | | | | |
| | | | | | | | |
| 160V, 50Hz | Asymmetrical air-gap Δ=0.5 mm | | | | | | |
| | | | | | | | |
| 160V, 50Hz | Asymmetrical air-gap Δ=1.0 mm | | | | | | |

**Figure 10.** Waveforms of variable component and harmonic analysis of magnetic pull axial forces; circumferential asymmetry of the air-gap, rated supply 400V, 50Hz: a, b) for symmetrical air-gap; c, d) for asymmetrical air-gap Δ=0.5 mm; e, f) for asymmetrical air-gap Δ=1.0 mm.

On the basis of the results shown in Table 5 and Figure 10 it may be concluded that increase in the circumferential asymmetry of the air-gap leads to significant increase of the fundamental harmonic
component due to magnetic field’s rotational speed (16.67 Hz), this is irrespective of the magnetic flux. This is also the reason for increased pulsations in the entire waveform of magnetic pull axial force. In case of remaining harmonics, it may be stated that circumferential asymmetry of the air-gap bears no impact on their amplitudes, and changes in these amplitudes are random. Therefore, if we want to diagnose the symmetry of the air-gap on the basis of axial force waveform, observation and analysis of the frequency component due to magnetic field’s rotational speed is the only information required.

6. Impact of asymmetry and magnetic pull forces on structural elements – numerical computations

In rotational machines, the main sources of rotor load are torsional moment, centrifugal force and force of magnetic pull, which occurs between rotor and stator surfaces. It has been demonstrated earlier, that distribution of magnetic pull force depends largely on uniformity and length of the air-gap between rotor/stator surfaces; in case of disk machines this force may attain significant values. Therefore, it is reasonable to take this load into account in mechanical calculations and to assess its impact on motor’s structural elements. It may be observed that most rotational machines operate under steady conditions. The variable conditions transpire usually when machine load or rotational speed changes; this happens most often during start-up or coasting. This is true in case of disk machines as well. When machine operates under variable conditions, the variable input functions appear; source of these inputs may be traced back to the machine itself, and the input forces are generated by rotating masses of residual unbalance of the rotor or they may be caused by varying distribution of magnetic pull forces due to e.g. circumferential asymmetry of the air-gap [8,9]. Hence, principal components of the input frequencies correspond to rotor’s rotational frequency and its harmonics. The appearance of destructive vibrations is related to resonance, which will manifest itself at the instant, when rotational frequency of the rotor is identical as natural frequency of the rotor-bearings-support system [8,9]. This frequency is also termed rotor’s critical frequency (resonance frequency). This frequency must be avoided; thus, natural frequencies of the rotor must be checked and machine design or rotational speed must be corrected, if necessary.

Examples of numerical analyses’ results (static and modal) for model machine AFIM11 are shown below; identical machine was previously tested. These analyses have been run on the basis of simplified 3D rotor models. We have used module for simple mechanical analysis, which is available in Autodesk Inventor Professional software. The restraints corresponding to rotor bearing and shaft neck torque output are shown in Figure 11. The applied load produced by rotational torque generated in the machine and magnetic pull is shown in Figure 12; magnetic pull has been previously recorded during tests of model machine with the help of four strain gauges EMS70-5kN. Mechanical strength of the rotor in the single stator machine (AFIM11) has been analysed assuming different settings of air-gap uniformity (different values of magnetic pull force at the circumference, corresponding to measured values).

![Figure 11. Boundary conditions (restraint)](image1)

![Figure 12. Boundary conditions (load torque Mo brand magnetic pull force F1-4)](image2)
Results of analysis for different load configurations are shown in Figures 13-16. These results contain information on reduced stress, dislocation and safety factor present and specific to constructional materials applied in rotor shaft and structural elements of rotor core.

**Figure 13.** Results of static analysis, motor loaded with torque 15 Nm and magnetic pull force $F_1-4=350N$; a) reduced stress, b) dislocations, c) safety factor.

**Figure 14.** Results of static analysis, motor loaded with torque 15 Nm and magnetic pull force $F_{1,2}=320N, F_{3,4}=420N$; a) reduced stress, b) dislocations, c) safety factor.
Figure 15. Results of static analysis, motor loaded with torque 15 Nm and magnetic pull force $F_{1-2} = 250$ N, $F_{3-4} = 490$ N; a) reduced stress, b) dislocations, c) safety factor.

Figure 16. Results of static analysis, motor loaded with torque 0 Nm and magnetic pull force $F_{1-2} = 250$ N, $F_{3-4} = 490$ N; a) reduced stress, b) dislocations, c) safety factor.

When results of simulations are analysed, it is clearly seen that stresses independently of assumed loads do not pose any hazard to rotor construction, and minimum safety factor for S235JR exceeds 5. Rotor construction is fairly rigid and rotor dislocation in case of analysed load does not exceed
0.01 mm. A problem may arise when load changes dynamically during motor rotation; at higher values it may influence the fatigue life of the rotor. The changing load generated by magnetic pull introduces a bending moment, which pulsates in accordance with rotational speed; in extreme cases this may lead to wear damage of rotor elements.

Results of modal analysis for six initial forms of natural frequencies are shown in Figure 17. The first critical speed of the rotor is equal to ~49 000 rpm; this is well outside machines speed range and there is no risk of resonance due to this critical speed.

**Figure 17.** Results of modal analysis – vibration forms (6 initial natural frequencies).

7. **Conclusions**

Results of calculations and tests of magnetic pull effect and asymmetry of the air-gap in disk induction motor with a single air-gap are presented in this paper. The results make it possible to determine values of magnetic pull axial force under different operating conditions as well as its changes accompanying variations in supply or load parameters. For all analysed motor operating conditions, the pulsation waveforms and their harmonic analysis are given. Hence, it was possible to determine the characteristic frequency components and their changes relative to changes in input quantities.

The presented data should be useful to machine designers working on bearing assemblies. The incorrect calculation of axial forces may lead to decreased machine efficiency and premature wear of bearings due to faulty selection. This may be traced back to unfavourable friction effects and excessive mechanical losses. These forces should be taken into account, when equivalent load of the bearings is calculated. The dependence between bearing durability and bearing load is exponential in character. If we neglect the axial forces, then bearings’ lifetime would decrease at least 3.33 times in relation to prognosis lifetime (s denotes the ratio of equivalent load to radial load). Hence, in such machines use of ball or angular contact cone bearings is recommended.

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