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# Investigation of properties of disk-type motor electromagnetic circuit using alternative materials in stator/rotor core.

***Streszczenie.*** *Zwiększenie efektywności energetycznej, ograniczenie kosztów produkcji lub zwiększenie gęstości mocy maszyn elektrycznych jest główną motywacją do poszukiwania innowacyjnych w tym zakresie rozwiązań konstrukcyjnych. Jednym z aspektów innowacyjności jest bez wątpienia wykorzystywanie alternatywnych materiałów, pozwalających na osiągnięcie danej korzyści czy to technicznej czy ekonomicznej. W niniejszym artykule przedstawiono oraz przeanalizowano różne rozwiązania konstrukcyjne obwodu elektromagnetycznego indukcyjnego silnika tarczowego wykorzystującego alternatywne materiały rdzeni stojana i wirnika. Przedstawiono wyniki obliczeń oraz wyniki badań laboratoryjnych modelowego silnika, którego rdzenie wykonane zostały między innymi z taśmy amorficznej, z blachy M470-50, z litej stali oraz z taśmy Vacoflux48 o wysokich wartościach indukcji nasycenia.* ***Badania właściwości obwodu elektromagnetycznego silnika dyskowego dla róa)nych materiałów stojana i wirnika***

***Abstract****. Improved energy efficiency, limitation of production costs or increased power density of electrical machines are among principal incentives in searching for new, innovative designs. Undoubtedly, one of innovation features is application of alternative materials, which results in accomplishment of required technical or economic advantages. Different design variants of electromagnetic circuit of induction disk-type motor have been presented in this paper; these variants use alternative materials for stator and rotor cores. Results of calculations and lab tests of a model motor have been given. Cores of the motor models have been made of amorphous strip, of M470-50 electrical sheet, of solid steel and of Vacoflux48 strip with high flux density saturation values.*

**Słowa kluczowe**: silniki tarczowe, silniki indukcyjne, materiały magnetyczne.
**Keywords**: axial flux motor, induction motor, magnetic materials.

## Introduction

In the design stage of modern electric drives, particular attention is paid to three issues: energy effectiveness (efficiency coefficient), power density in relation to weight and production costs. These issues are directly related to each other; however, in a sense they are also opposed. In general, increase of energy effectiveness may be accomplished by:

a) increasing the amount of active materials in the machine, which simultaneously decreases power density and raises production costs or

b) application of modern materials, which in turn leads to increase in power density, but usually results in significant rise of production costs.

This general approach neglects lots of other factors, such as processing, optimization of electromagnetic circuit etc. This viewpoint is presented in order to draw attention to the necessity of finding a satisfactory compromise as early as in the design stage of the machine; a happy medium between the enumerated problems.

The selection of material magnetic for stator/rotor core [1] is without doubt one of key factors influencing all of these issues. The current paper presents characteristics of induction disk-type motors with cores manufactured in accordance with following design variants:

1. stator/rotor core is made of generator strip M470-50A 0.5 mm thick,
2. stator core is made of generator strip M470-50A 0.5 mm thick, rotor core is made of solid steel S355J2,
3. stator core is made of amorphous strip 25 μm thick, rotor core is made of generator strip M470-50A 0.5 mm thick,
4. stator core is made of Vacoflux48 strip, rotor core is made of generator strip M470-50A 0.5 mm thick.

It must be stressed that in case of every design variant, the shape and dimensions of magnetic circuit, winding data and constructional elements are identical. The only difference is type of material used for stator or rotor core.

Basic data and parameters of the investigated motor model are shown in Table 1.

Table 1. Basic constructional data of disk-type motor

| **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 |
| 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 |

The design assumption for using amorphous strip 0.25 μm thick was limitation of iron loss on account of very low lossiness of amorphous material [2,3,4,5,6]. On the other hand, manufacturing rotor out of solid steel simplifies technological process (cutting and rolling the strip are not required) and so theoretically lowers the production costs [7]. If we consider that in asynchronous motor rotor's magnetic field pulsation frequency is low (2-5 Hz), use of solid steel may be justified in some cases. Use of strips with high flux density saturations aims at increasing power density and improving efficiency coefficient of the machine.

Measurement results of lab tests conducted for three of the discussed models are presented in the paper. Tests have been run in order to verify theoretical assumptions. Technological processes used in manufacture of different motor variants have also been analysed and assessed together with economic aspects.

In case of design #4, i.e. model with stator core made of Vacoflux48 band, only theoretical calculation results are given.

Physical properties and appropriate characteristics of different materials are presented e.g. in publication [2].

**Model # 1 –stator and rotor made of M470-50A steel strips**

The first variant design is model of disk-type induction motor, with stator and rotor core made of generator strip roll M470-50A 0.5 mm thick. This is a reference for the remaining considered cases, since this material is most commonly used. Technology of manufacturing stator core is as follows: the roll of generator strip is wound around a dedicated mandrel (this remains in the machine afterwards as a constructional element) and slots are then cut out with electro-erosion (spark erosion) method. The cost of manufacturing the roll for the discussed motor (including the raw material) did not exceed *c.*25 €. On the other hand, the electro-erosion method is expensive and time-consuming, its cost was *c.* 500-700 €. Fragment of finished stator core after machining is shown in Fig.1.

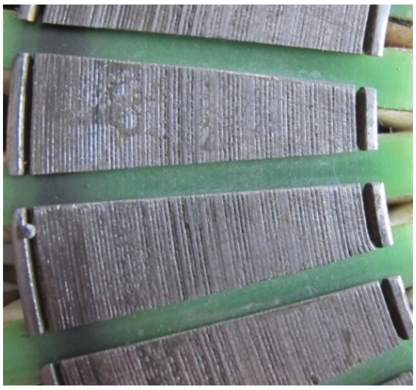

Fig.1. Fragment of stator core made of M470-50A strip - after electro-erosion machining.

Rotor core has also been manufactured from M470-50A strip roll; technology is identical as for stator core. Casts of aluminium cages together with end rings have then been executed. The assembled rotor core with cage cast and end-rings is shown in Fig.2.

Fig.2. Cage rotor of disk-type induction motor; rotor is made of M470-50A strip, cage bars and both end-rings are visible.

**Model # 2 –solid steel rotor**

The second analysed design variant is a motor model with stator core identical as in model #1, while rotor core has been made of solid steel S355J2; dimensions and shape of magnetic circuit have remained unchanged. Turning of ring (rotor core) lasted for about 4-5 man-hours; therefore, cost of solid ring has not been decreased (this was initially assumed). The finished ring has been subjected to slot cutting by electro-erosion method, and afterwards aluminium cage has been manufactured. On account of solid steel material, electro-erosion of slots is much faster and the quality of the finished product is better than in case of strip-rolled core. This is due to the absence of insulation coatings, which exist in rolled strip; when the strip is subjected to electro-erosion, these coatings are an additional complication. Rotor core made of solid steel (without aluminium cage) is shown in Fig.3.

Fig.3. Rotor cage made of solid steel

**Model # 3 –stator made of amorphous tape**

The third investigated design variant is a motor model with stator core made of amorphous strip 25 μm thick. Lossiness of amorphous strip is significantly lower than lossiness of standard electrical sheets [3,4,5,6]. Fragment of ring is shown in Fig.4, electro-erosion has not been executed yet. After rolling, the ring has been subjected to thermal processing and then glued together with the help of dedicated resin. The cost per unit of manufacturing ring, materials included, is *c.* 500€.

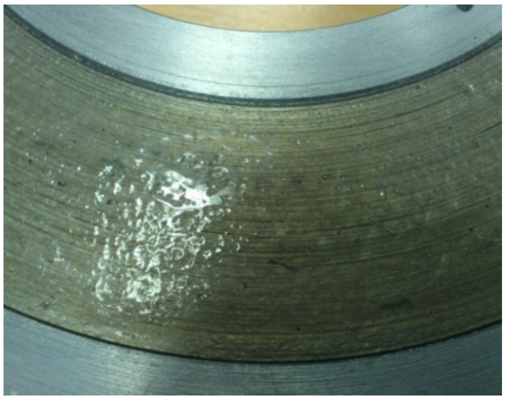

Fig.4. Fragment of stator core roll made of amorphous strip.

Afterwards, the core has been subjected to electro-erosion processing. The photo of core fragment after processing is shown in Fig.5.

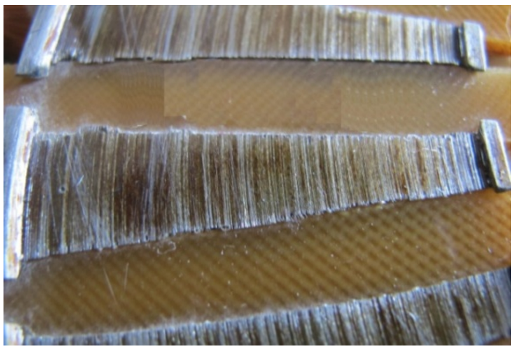

Fig.5. Fragment of stator core made of amorphous strip - after electro-erosion machining.

Electro-erosion machining of the amorphous strip core was very tedious. We may presume that resin gluing together several layers of strip hindered the processing. As a result, the precision of worked edges along the cut lines has not been satisfactory. It may be observed from Fig.5 that substantial warps and pits are present along the worked-out tooth edges.

**Model # 4 - Vacoflux48 strip stator**

The fourth investigated design variant is motor model with stator core made of Vacoflux 48 strip characterized by high value of saturation flux density. In this case a physical model has not been executed; impact of material on motor performance has been analysed with the help of computational model only. First of all, Vacoflux48 material is characterized by high value of flux density saturation (*c.* 2.2 T) and, in relation to standard strips, its lossiness is lower.

Replacement of armature made of standard electrical strip e.g. M470-50A with armature made of strip characterized by high values of flux density saturation has a significant impact on parameters and characteristics of disk-type induction motor. This issue may be handled in two different ways. In the first approach, a direct replacement of the stator core material is executed; there is no change in magnetic circuit geometry or winding data. Changes due to application of different magnetic materials may be observed when characteristics dependent on varying supply voltage are constructed (supply frequency is constant); under such conditions, the magnetic flux varies. The curves showing the influence of this change of efficiency coefficient of the motor are shown in Fig.6.

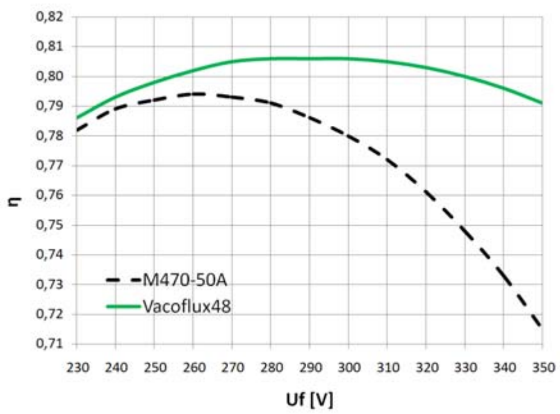


Fig.6. Efficiency vs. supply voltage at constant frequency 50 Hz for disk-type induction motor rated at 1.5 kW; strip M470-50A and strip Vacoflux48_0.35mm.

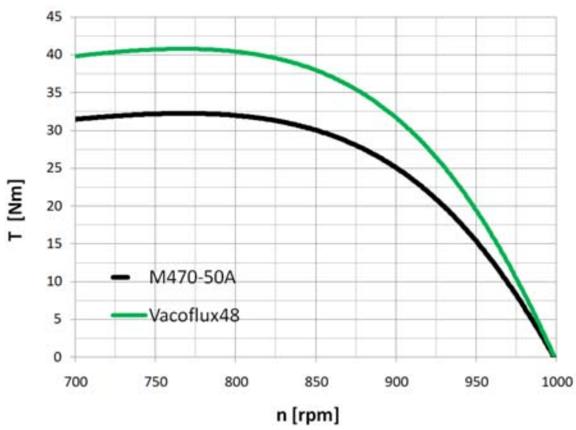


Fig.7. Torque at shaft vs. rotational speed for disk-type induction motor rated at 1.5 kW; strip M470-50A and strip Vacoflux48_0.35mm.

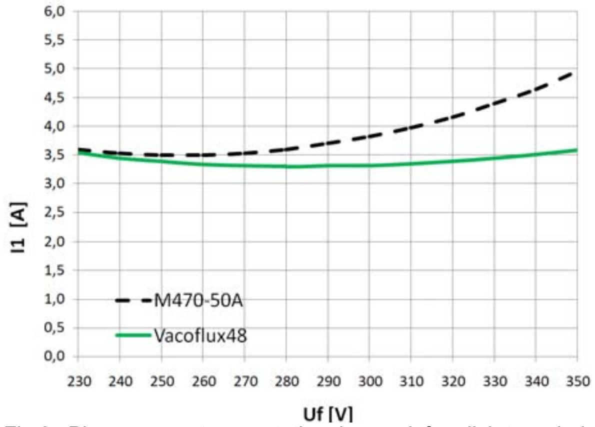


Fig.8. Phase current vs. rotational speed for disk-type induction motor rated at 1.5 kW; strip M470-50A and strip Vacoflux48_0.35mm.

The analysis method presented above and related to impact of change in armature core magnetic material is justifiable for research purposes only. In order to compare two motors with different stator core materials correctly, the desired final effect must be defined in the design stage and then each machine must be fitted with a different electromagnetic circuit; reference point in the form of selected physical quantities will be maintained as constant. The following assumptions may be taken: supply parameters, rotor winding data and geometry of stator magnetic core; stator winding data is subject to change. Characteristics showing the impact of armature material are shown in Fig. 7 and 8 (assumptions as defined above).

It may be stated on the basis of the conducted analysis, that:

- direct replacement of standard band M470-50A with a high saturation Vacoflux48 band, not accompanied by changes in geometry and winding data of the stator, leads to limitation of idle run current value, limitation of phase current, higher power factor cos φ and higher efficiency, when *U/f* values are increased;
- proper design of motor with stator core made of high saturation strip will make it possible to obtain higher (even by 25%) values of rated torque and maximum torque (in comparison to standard design with M470-50A strip)while weight and dimensions of the machine remain unchanged. Motor efficiency and multiplicity of start-up torque will also be increased.

**Idle run**

Idle run curves for sinusoidal voltage supply have been measured for three design variants. Tests have been carried out for different supply frequencies (up to 200 Hz); however, for frequencies higher than 50 Hz it was not possible to supply motors with full voltage, since motors have been rated at 400V, 50 Hz. Therefore, for highest frequency values the supply voltage has been limited to *c.*200 V; relative value of main magnetic flux has then been equal to *c.* $\Phi_{wzg}$ = 0.3.

The relationship between magnetizing current and supply voltage for the discussed design variants is shown in Fig.9. It is obvious that the highest reluctance (and worst magnetizability) is demonstrated by solid steel rotor variant. For the amorphous stator core, the non-linear curve fragment is attained sooner than in case of reference model.

Comparison of iron losses versus supply voltage at idle run and frequency 50 Hz for discussed supply variants is shown in Fig.10. When main magnetic flux is nominal (400V, 50 Hz), iron losses for motor with solid steel rotorare by *c.* 70% higher than for motor with stator/rotor cores made of standard M470-50A band. The increased losses are due to higher additional losses in solid steel rotor core [8]. Unfortunately, the losses in amorphous stator core are also slightly higher, while it was expected that they would be significantly lower. When the results and references have been studied again, it has been found that the probable reason is the electro-erosion cutting of amorphous strip. This has caused a substantial deterioration of material properties [3,4,5]. Thus, it may be concluded that use of amorphous strip in the adopted manufacturing technology of disk-type motors does not yield expected results since mechanical machining is required.

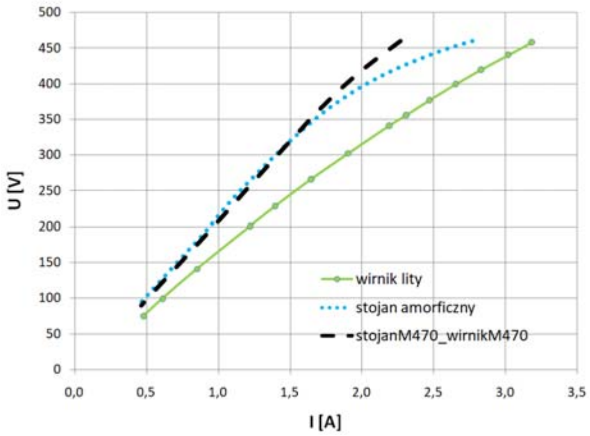


Fig.9. Comparison of magnetizing current vs. supply voltage

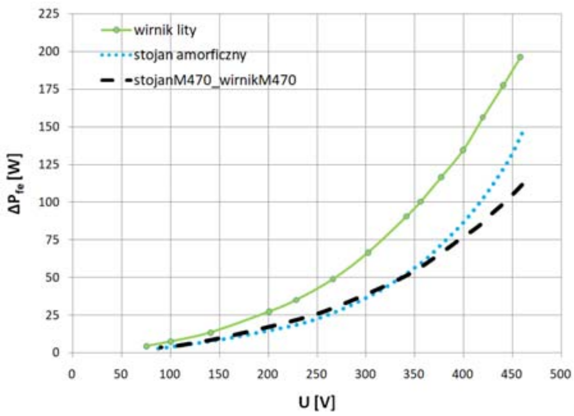


Fig.10. Comparison of iron losses vs. supply voltage at idle run, frequency 50 Hz

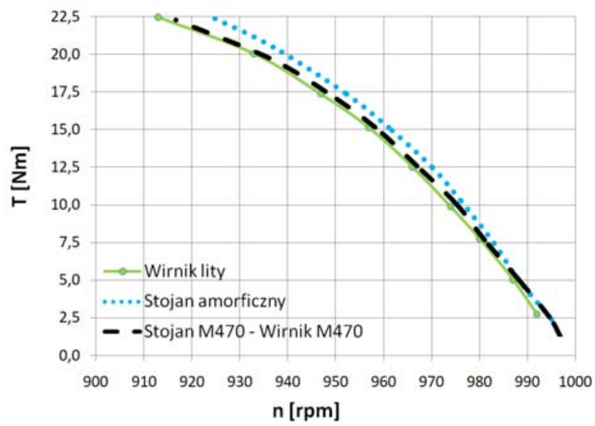


Fig.11. Torque vs. speed curves for different motor models, sinusoidal supply 400V, 50Hz.

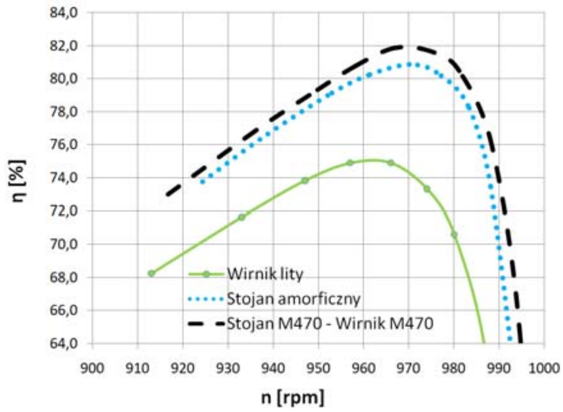


Fig.12. Efficiency coefficient η vs. rotational speed (slip) curves for different motor models, sinusoidal supply 400V, 50Hz.

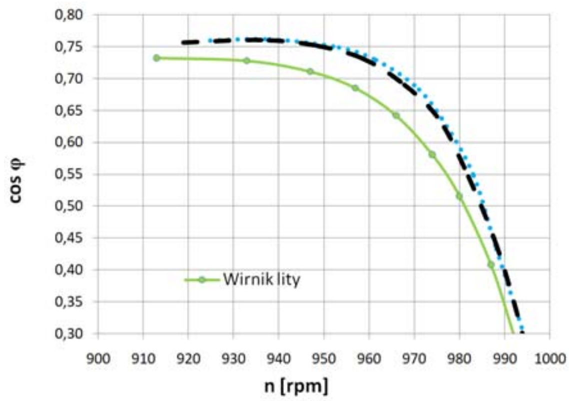


Fig.13. Power factor cosφ vs. rotational speed (slip) curves for different motor models, sinusoidal supply 400V, 50Hz.

Lab tests for all model motors have been run, with rated supply 400V 50Hz, and load torque up to 22.5 Nm (1.5 $T_n$). The obtained torque-speed curves are shown in Fig.11.

Efficiency and power factor curves for different design variants are shown in Figs. 12 and 13. The highest efficiency in the entire rotation speed (load) range is demonstrated by motor model with stator/rotor core made of M470-50A band. Efficient of motor with solid steel rotor is significantly lower than efficiency of other models. Motor with solid steel core rotor shows also much lower power factor cosφ.

Comparison of basic parameters of the discussed motor models is shown in Table 2. It has been assumed that stator current does not exceed the rated value (which has been determined previously and equals 3.7 A. This has been calculated on the basis of temperature rise during heat run test with Δϑ=80 K).

Table 2. Operational parameters for different motor models for rated stator current

| | I1 [A] | T [Nm] | n [rpm] | η [%] | cosφ |
|---|---|---|---|---|---|
| M470 | 3,7 | 15,0 | 959 | 80,9 | 0,72 |
| Solid rotor | 3,7 | 13,3 | 963 | 75,0 | 0,66 |
| Amorphous stator | 3,7 | 15,6 | 959 | 80,0 | 0,72 |

In case of stator current equal to 3.7 A, solid rotor motor torque is by *c.* 12% less than in case of reference model, while the model with amorphous stator core is characterized by torque higher by *c.*4%.

From a different viewpoint, when identical load torques are applied, operational parameters of motor models are also interesting. These parameters are set out in Table 3; load torque for all design variants has been assumed to be equal to 15 Nm.

Table 3. Operational parameters for different motor models; identical load torque

| | I1 [A] | T [Nm] | n [rpm] | η [%] | cosφ |
|---|---|---|---|---|---|
| M470 | 3,7 | 15,0 | 957 | 80,9 | 0,72 |
| Solid rotor | 4,0 | 15,0 | 962 | 74,8 | 0,69 |
| Amorphous stator | 3,6 | 15,0 | 959 | 80,3 | 0,73 |

We may conclude from data presented in Table 3 that loading the solid steel rotor motor with 15 Nm torque produces a rise of stator current up to 4 A, which in turn will lead to increased winding temperature (by *c.*16%).
On the basis of measurement results, the total power losses have been divided into appropriate types of losses for each motor model. Rotor losses have been calculated with the help of the following formula:

$$(1) \qquad \Delta P_2 = (P_1 - \Delta P_{cu1} - \Delta P_{Fe}) \cdot s$$

where: $\Delta P_2$ – rotor losses, $P_1$ –input power, $\Delta P_{cu1}$ –stator copper losses, $\Delta P_{Fe}$ –iron losses at idle run.

Then, when total losses are known, we may determine remaining additional losses using the following relationship:

$$(2) \qquad \Delta P_d = \Delta P - \Delta P_{cu1} - \Delta P_{Fe} - \Delta P_2 - \Delta P_m$$

where: $\Delta P$–total losses, $\Delta P_d$–remaining additional losses, $\Delta P_m$–mechanical losses.

Rotor losses $\Delta P_2$ for different design variants are shown in Fig.15. In case of rated load ($P_m$ = 1500 W) rotor losses for all design variants are approximately the same (difference varies from 64 to 71W).

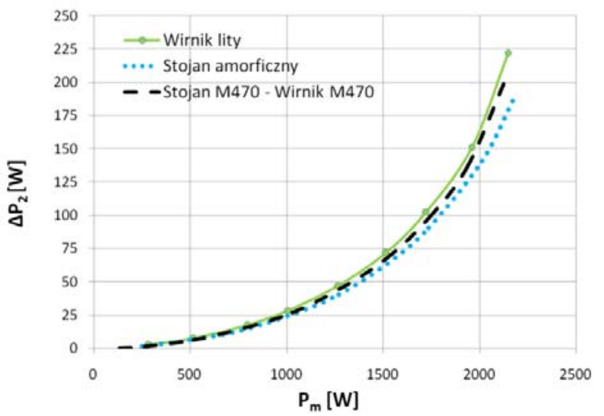


Fig.14. Comparison of rotor losses vs. load power (power at shaft) for different design variants.

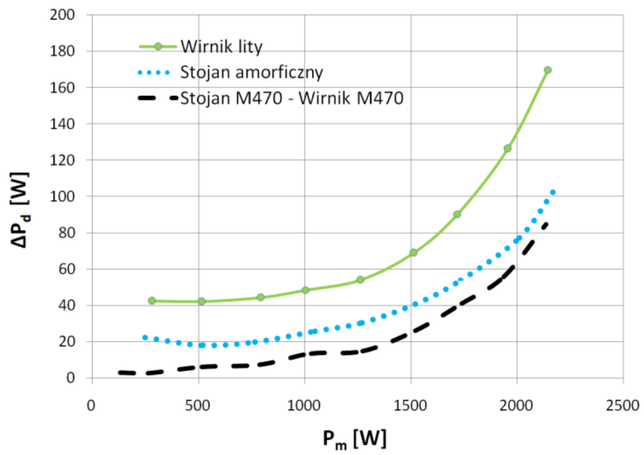


Fig.15. Comparison of remaining additional losses vs. load power (power at shaft) for different design variants.

Comparison of additional losses $\Delta P_d$ for different design variants is shown in Fig.15.

Basing on Fig.15 we may state that the lowest additional power losses are present in model of motor with stator/rotor cores made of M470-50A strip, while the highest losses (about three times as high for rated load) are displayed by the model using solid steel rotor.

**Conclusion**

Four different design variants of disk-type induction motor have been presented and compared in the paper. The variants differ by magnetic materials used in construction of stator or rotor core. Use of selected and different magnetic materials was aimed at limiting power losses, increasing efficiency, increasing power density or limiting production costs. Results obtained during actual tests with physical models show that:
1. Application of materials characterized by high flux density saturations makes it possible to achieve higher values of rated and maximum torque compared to standard execution with M470-50A strip. Difference may be as high as 25%, while weight and dimensions of the machines remain unchanged. Higher multiplicity of start-up torque and higher efficiency are also obtained.
2. Production cost for rotor core made of M470-50A strip roll is not higher than for rotor with solid steel core.
3. In case of solid steel rotor, operational parameters including efficiency are significantly worse than in case of motor with stator and rotor cores made of M470-50A strip.
4. In case of motor with stator core made of amorphous strip, stator iron losses are not less than for core made of M470-50A strip. This is due to electro-erosion machining carried out in order to produce slots.
5. Cost of amorphous strip core is much higher than in case of core made with standard M470-50A strip. Moreover, processing of amorphous band core is very strenuous.
To conclude, comparison of the presented design variants shows that the best solution from economic, technical and technological viewpoint is the variant of motor with stator/rotor cores made up of standard M470-50A strip 0.5 mm thick.

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