On the possibility of unification of synchronous motors with permanent magnets with asynchronous motors of general application

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Abstract The use of modern high-coercive permanent magnets in synchronous motors allows one not only to unify the design and technology of their fabrication with asynchronous motors of general application, but also to significantly increase the efficiency of electric drives of production equipment and quality of technological processes. The performed studies have led to the conclusion that this problem is effectively solved by reconstructing only the active part of the rotor of an induction motor.

1. Introduction
Asynchronous motors (AM) of general use are in large numbers produced in the world and widely used in technological equipment drives. It is sufficient to say that they account for 60–70% of the total generated electricity. However, they are characterized by a relatively low power factor [1], and therefore considerable resources are spent on the production of reactive energy. This problem is exacerbated by the fact that in most cases, AM work at underload, which leads to reduction of their power factor. The task could be solved by replacing them by synchronous motors, but the problem of starting and synchronizing these machines with the network makes it difficult to solve.

Attempts were made to replace AM by synchronous reluctance motors [2], which are characterized by a successful combination of the ease of start-up and the complete absence of mechanical contacts. However, these motors are not widely used as they do not solve the problem of energy saving.

There also exist synchronous electric motors with excitation from permanent magnets (SMPM) [3,4], which are non-contact and easy to start. However, the power of these motors was limited to dozens of watts due to the relatively low specific energy of the applied permanent magnets of the brands ALNICO and others, which are weakly resistant to the demagnetizing action of the magnetizing force of the stator winding.

The appearance of samarium-cobalt high-coercive magnets or neodymium-based magnets (NeFeB) created conditions for studying the possibility of creating competitive SMPM [5]. In terms of addressing this issue, the task was set to investigate the possibility of modifying the design of general-purpose AM and expanding the use of synchronous motors.

2. Modernization of the design
Our research was based on the 4A100L4 serial four-pole motor [6], which has a wide variety of applications and its parameters and characteristics are headlined for example, in [6]. Fig. 1.a) shows a cross-section of this motor rotor. Here we designated: 1 is a sheet of a magnetic circuit, 2 is a core of a short-circuited winding, 3 is a rotor shaft.
The modernization of the AM design was reduced to the placement of four permanent magnets on the rotor, indicated by position 4 in Fig. 1(b), (c) and (d). Consider these options in more detail.

Figure 1. Modernization of the rotor design: a) Rotor of the asynchronous motor; b) SM rotor with internal magnets; c) SM rotor with embedded magnets; d) SM rotor with superposed magnets.

### Table 1.

| Model type | Magnet height $h_m$ mm | Shaft power $P_2$ W | Consumed active power $P_1$ W | Rotation frequency, $n$ rpm | Consumed current $I$ A | Efficiency | $\cos \phi$ |
|------------|------------------------|---------------------|-------------------------------|----------------------------|------------------------|------------|-----------|
| 4A100L4    | -                      | 3940                | 4169                          | 1475                       | 9.8                    | 0.945      | 0.659     |
| SMPM-1     | 14                     | 4006                | 4348                          | 1500                       | 14.9                   | 0.92       | 0.47      |
| SMPM-2     | 16                     | 4006                | 4306                          | 1500                       | 13.7                   | 0.93       | 0.49      |
| SMPM-3     | 17                     | 4006                | 4319                          | 1500                       | 14.2                   | 0.93       | 0.472     |

The design of the SM rotor, shown in Figure 1(b), is well analyzed in [3,4], and it is recommended for permanent magnet synchronous motors (SMPM) if necessary to increase the power of the machine. Here, magnets 4 in the form of neodymium-based magnet segments are placed directly on the rotor shaft. The asynchronous part of the rotor covers a block of magnets and contains a short-circuited winding in the grooves, which provides the minimum gap between the rotor and the stator. Such design provides a reliable start, acceleration, and synchronization of the rotor [2-4]. To reduce the dissipation of the magnetic field of the magnets, grooves 5 are made in the back of the asynchronous part with bridges orienting parts of the rotor sheet relative to each other.

The studies were carried out using mathematical models based on the finite element method. In order to achieve the best motor performance, we considered various combinations of sizes of the following active elements of the rotor: the radial size of the magnet $h_m$, the height of the groove, the width of the tooth. A combination of sizes was selected to provide the best energy performance of the machine. The results of the analysis are shown in Table 1. Here, for clarity, the characteristics of the four models are presented. The first line presents the results of a prototype simulation, namely the 4A100L4 asynchronous motor, which confirms the model adequacy. Further we present the characteristics of the motor with permanent magnets in accordance with Fig. 1(b), where the magnets are surrounded by an asynchronous part of the rotor. From the obtained results the following can be concluded: the design of rotor with “internal” magnets ensures reliable start-up and synchronization of the motor. The best characteristics are obtained when the magnet height is $h_m=14$ mm.

At the same time, in synchronous mode, the motor is worse than the prototype in terms of the energy characteristics, in particular, in terms of power factor $\cos \phi$. This may explained by the lack of excitement of the machine in synchronous execution. If we assume that the magnet volume here is sufficient for the required degree of excitement, then the result can be attributed to the field dissipation by the asynchronous rotor elements.

Attention was drawn to the solution of the problem according to [5, 7, 8], where the magnets are “embedded” in the body of the rotor magnetic circuit. This solution is used in the design shown in Fig.1c), where the magnets 4 are placed on the cylindrical surface of the rotor while maintaining its...
dimensions. The sizes of magnets and other structural elements are selected from the conditions for achieving the best energy characteristics. The results are shown in table 2.

| Table 2. |
|---------------------------------|-------|-------|---------------|-------|-------|--------|
| Model type | Magnet height $h_m$, mm | Shaft power $P_2$, W | Consumed active power $P_1$, W | Rotation frequency, $n$, rpm | Consumed current $I$, A | Efficiency $\text{Cos}\phi$ |
| SMPM-4 | 5 | 4006 | 4408 | 1500 | 9.07 | 0.91 | 0.75 |

It is reasonable to make the comparative estimation of the obtained result using the so-called “power efficiency” [3, 9]:

SMPM-2 (internal magnet): $\eta \cdot \text{Cos}\phi = 0.4557$

SMPM-4 (embedded magnet): $\eta \cdot \text{Cos}\phi = 0.6825$

The obtained positive result is significantly different, which allows us to conclude that the constructions with the magnets placed under the magnetic core is not energy efficient and therefore the structures with an external magnet should be considered.

The design with the so-called “superposed” magnets was also considered [8, 10-12], for which the magnets are placed on the outer cylindrical surface of the rotor (Fig. 1d). The results of the model study are given in table 3. Here the energy efficiency is:

$\eta \cdot \text{Cos}\phi = 0.9504,$

which makes this construction interesting for further consideration.

| Table 3. |
|---------------------------------|-------|-------|---------------|-------|-------|--------|
| Model type | Magnet height $h_m$, mm | Shaft power $P_2$, W | Consumed active power $P_1$, W | Rotation frequency, $n$, rpm | Consumed current $I$, A | Efficiency $\text{Cos}\phi$ |
| SMPM-4 | 5 | 4006.6 | 4248 | 1500 | 6.17 | 0.99 | 0.96 |

**Figure 2.** The magnetic field of the rotor coupled to the stator winding:

- a) rotor with superposed magnets;
- b) rotor with embedded magnets.

The degree of excitation of the considered SMPM variants can be estimated by comparing the magnitude of the magnetic flux driven by the permanent magnets of the rotor. Figure 2 shows the magnetic field curves of the rotor pole coupled to the de-energized stator winding. Under the figure we show the corresponding values of the magnetic flux $F_{pol}$. It is clearly seen that the transition to the
“superimposed” magnets, ceteris paribus, makes it possible to increase the excitation of the machine by almost 13%, which can explain the significant improvement in the energy characteristics of the machine.

3. Start-up characteristics
It is interesting to study the quality of the motor start [13-15] after the modernization of the rotor. Figure 3 shows curves for time-dependence of rate during start-up for the basic and the upgraded motor structures discussed above. It is clearly seen that at start-up, the quality of acceleration of a motor with internal magnets practically does not differ from the prototype taken. The transfer of magnets to the outer surface of the rotor led to some delay in acceleration, which can be associated with noticeable adjustments to the “squirrel cage”.

![Figure 3. Comparison of the rotor acceleration curves for the basic and the upgraded versions of the electric motor.](image)

The obtained result, showing that in all variants of modernization the motor is reliably started and synchronized is attracting attention.

Conclusions
As a result of the conducted study, we can conclude that, taking into account the modern possibilities of using high-energy permanent magnets, it becomes possible to upgrade general-purpose asynchronous motors with their translation into synchronous operation mode. This does not require large costs for the adjustment of the design and technological preparation of production. The obvious benefit of such a modernization is in tangible energy savings, and improvement of the technological parameters of the production equipment motors.

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