Electric machines with axial magnetic flux

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Abstract. The paper contains information on the performance of axial machines compared to cylindrical ones. At the same time, various constructive schemes of synchronous electromechanical converters with permanent magnets and asynchronous with short-circuited rotor are presented. In the developed constructions, the aim is to maximize the usage of the material of the stator windings. The design elements of the axial machine magnetic system are presented. The FEMM application depicted the array of the magnetic field of an axial machine.

1. Introduction

The study of the axial electric machine, little researched in the past, is a theoretical and practical interest for their design and production in order to increase the efficiency of their use in relation to the use of the cylinder machine with radial magnetic flux.

In this context, the interest refers to the performance of the electric machine with axial magnetic flux relative to the radial magnetic flux.

At present these performances are obvious, namely: reduced axial dimensions, use of cold rolled steel with reduced magnetic losses, reduction of stamping waste, increased stator and rotor cooling surface removed from the stator package, possibility of replacing the mechanical rigid coupling between Stator and rotor with magnetic one.

Some of these performances, particularly eloquent, are seen in the use of axial magnetic flux motors to drive certain mechanisms: centrifugal electric pumps, fans, and, when used as generators, can be driven by wind and water turbine engines. When coupling the axial machines with the above-mentioned mechanisms, the rotor can be cumulated with the traction or drive mechanism, thus making it possible to couple and compensate the unilateral electromagnetic forces between the stator and the rotor. Moreover, in these machines it is possible to obtain reduced angular velocity, since the diameter is increased, allows the stamping of a large number of notches and hence a large number of poles.

The purpose of the paper is to study the construction of synchronous electric machines with axial flux with permanent magnets; the study of stator windings used in electric machines with permanent magnet rotors and the use of inexpensive axial machine manufacturing technologies.

2. Electromechanical converters of various constructions

According to the studied and analyzed sources [1], [2], it was concluded that this type of machines can be classified as follows: with a disc rotor or with multiple disk rotors; with a rotor and a stator, with flat winding on the stator (Figure 1); with two rotors and a toroidal winding stator (Figure 2);
In most cases, the disc rotor design schemes are proposed for use in automated systems. These motors simultaneously solve two problems: they reduce the moment of inertia and minimize the unilateral forces between the stator and the rotor.

The use of permanent magnets fixed on the rotor allows to obtain a synchronous electromechanical converter. This electric machine has high performance such as: efficient copper use or increasing the length of the active parts of the stator winding. This type of machine can be used in generator mode and in synchronous motor mode (Figure 3).

Axial synchronous generators can be used to generate electricity at wind or hydraulic micro-power plants. They can be used at low speeds and are mechanically coupled directly to the drive motor.

When manufacturing synchronous generators, the active part can be used more efficiently, thus increasing the power of the machine. This can be done by optimizing the construction of synchronous generators.

In Figures 4 and 5 there are schematically shown the constructions of two electromechanical converters with one and two rotors respectively. In both machines, three active parts of the stator windings are effectively used, thus increasing the machine’s power in the same volume.
Figure 3. Axial electric machines with two stator and two rotor windings.

Figure 4. Synchronous axial machine with one rotor.

Figure 5. Synchronous axial machine with two rotors.
For maximum use of the active material (stator winding), the most efficient would be the use of horseshoe magnets on the rotor (Figures 6 and 7).

The toroidal winding used in two-rotor axial machines is difficult to achieve from a technological point of view. This has resulted in the construction of the hybrid winding, which is easy to make (Figure 8).

**Figure 6.** Synchronous axial machine with one rotor

**Figure 7.** Synchronous axial machine with two rotors

**Figure 8.** Stator axial construction packages with different types of windings:
   a) toroidal winding; b) hybrid wrapping
3. Elements of electromagnetic calculation of an asynchronous axial motor with one rotor

The distinctive feature of the electromagnetic calculation for the single-phase axial motor is its equivalence with the cylindrical asynchronous machine.

This equivalence was achieved by determining the ratio between the mean diameter of the axial machine stator pack and the inner diameter of the stator pack of the cylindrical machine. This connection is made using the electric machine constant - Arnold.

The treatment of electromagnetic computation in this way gives the possibility to use some recommendations, graphical interpretations for the calculation of the cylindrical machine. However, the axial machine electromagnetic calculus is not reduced to the direct use of straightforward recommendations for ordinary asynchronous machines, here the results of the research done in the field of axial machines were applied using classical design methods of normal and special electrical machines [3-5].

3.1. Determination of basic geometric dimensions

Below are some calculation elements of the basic dimensions of the axial asynchronous motor with one rotor and flat winding on the stator.

The calculation of power of the single-phase motor is determined by the following relationship:

\[ P = \frac{k_e \cdot P_n}{\eta_n \cdot \cos \phi_n} \]

(1)

where \( k_e \) – The coefficient of the electromotive voltage, proportional to the ratio \( \frac{E_1}{U_1} \) [6].

In the asynchronous machine one of the basic geometric dimensions is the internal diameter of the stator. To perform the calculations for the axial single-phase motor it is necessary to equalize the single-phase motor with the classic cylindrical engine [7].

Several tests carried out within the Electromechanical Department, of the Technical University of Moldova, in this direction obtained the expression for the average diameter of the axial motor:

\[ D_m = \frac{P_1 \cdot 2p}{k_B \cdot \lambda_\delta \cdot \pi \cdot k_{W1} \cdot B_\delta \cdot A} \]

(2)

where \( \lambda_\delta = \frac{l_\delta}{\tau_m} \), but \( \tau_m = \frac{\pi \cdot D_m}{2p} \)

The length of the stator packet calculation:

\[ l_\delta = \frac{P_1}{k \cdot k_B \cdot k_{W1} \cdot D_m^2 \cdot A \cdot B_\delta \cdot \Omega} \]

(3)

where \( k = k_T \beta \), \( \beta = (1.25 - 1.7) \) it is recommended to set the power reduction of the single-phase motor compared to the three-phase motor;

\( k_T = 2 \) – Indicates the efficiency of axial engine cooling

The values of the magnetic induction \( B_\delta \) and the linear load of current \( A \) vary between \( B_\delta = (0.5 - 0.7) \) T, and the linear current load \( A = (20 - 30) \cdot 10^3 \) A.

The outer and inner diameter of the stator packet

\[ D_E = D_m + l_\delta \quad \text{and} \quad D_i = D_m - l_\delta \]

(4)
Phase nominal current:

\[ I_n = \frac{P}{\sqrt{2}U_n} \]  

Number of notches for pole and phase

\[ q = \frac{Z_1}{2pm_i} \]  

and the number of conductors in a notch:

\[ N_c = \frac{\pi D_m \cdot A}{Z \cdot I_n} \]  

Number of turns in the main phase winding:

\[ W_1 = \frac{N_c \cdot Z_1}{m_1 \cdot 2a_1} \]  

where \( a_1 \) – number of current paths.

Magnetic flux closed through the engine air gap:

\[ \Phi = \alpha_s \cdot \tau_m \cdot l_\delta \cdot B_\delta \]  

The number of turns in the main phase is specified with the relationship:

\[ W_A = \frac{k_c \cdot U_n}{4k_B \cdot f \cdot k_{w1}} \]  

Also, the number of conductors in the notch is verified

\[ N_C = \frac{2m_1 \cdot W_A \cdot a_1}{Z_1} \]  

The linear current load is checked:

\[ A = \frac{N_c \cdot I_{in} \cdot Z_1}{\pi \cdot D_m} \]  

and the average value of the axial motor diameter [4]:

\[ D_m = \sqrt[3]{\frac{P \cdot k_E}{k \cdot k_B \cdot k_{w1} \cdot \Omega \cdot B_\delta \cdot A \cdot \eta_n \cdot \cos \phi_n \cdot l_\delta}} \]  

Number of teeth corresponding to the diameters \( D_E, D_m, D_1 \) - outer, medium, inner.

\[ t_{Z1} = \frac{\pi D_E}{Z_1}; \quad t_{Zm} = \frac{\pi D_m}{Z_1}; \quad t_{Z2} = \frac{\pi D_1}{Z_1} \]  

The density of the current in the stator winding is selected depending on the motor execution and varies within the limits \( \Delta_1 = (5 \text{-} 10) \frac{A}{\text{mm}^2} \) .
Cross sectional area of the phase conductor $A$:

$$S_A = \frac{I_{ln}}{\Delta I}$$  \hspace{1cm} (15)

The width of the tooth is determined by the expression:

$$b_{Z1min} = \frac{B_{\delta} \cdot t_{z1} \cdot I_{\delta}}{B_{Z1max} \cdot I_{\delta} \cdot k_{Fl}}$$  \hspace{1cm} (16)

then the width of the notch:

$$b_{C1} = t_{z1} - b_{Z1min}$$  \hspace{1cm} (17)

the area of the notch section occupied by the conductors is calculated, then determine the coefficient of filling of the stator groove:

$$k_{U} = d_{IZ}^2 \cdot N_C \cdot S_{C1}$$  \hspace{1cm} (18)

where $d_{IZ}$ is the diameter of the insulated conductor, $S_{C1}$ - the area of the notch without insulation

4. Magnetic field analysis in synchronous machines

For determining and specifying the parameters of the proposed synchronous machine, it is necessary to determine the magnetic field produced by windings currents. In this context, the finite element method with FEMM is used [8].

Figure 9 shows the result of the magnetic field analysis of the synchronous machine with toroidal stator winding and permanent magnets on the rotor. In this case the synchronous machine with stator magnetic core was analyzed.

Figure 9 Magnetic field analysis of the axial construction machine with notches on the stator:

a) The field of the magnetic field; b) Magnetic induction curve in the air gap

In order to minimize the action of higher order harmonics, the geometric configuration of the magnetic poles has been modified, so the magnetic induction curve of the practical sinusoidal in the air gap can be obtained, assuming that the stator is made without notches (Figure 10).
5. Conclusions

- Constructive designs schemes of axial electric machine were analyzed.
- The optimization of synchronous machines with permanent magnets with one rotor or two have been studied.
- The types of stator windings that can be used on synchronous machines with permanent magnets are described.
- The FEMM analysis showed that by modifying the construction of the pole magnets and the stator pack, the induction curve of the air gap is practically sinusoidal.

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