Electromechanical converters for electric vehicles

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Abstract. The paper presents the analysis of various constructive schemes of synchronous electromechanical converters with permanent magnets fixed on the rotor and asynchronous with the short-circuit rotor. Various electrical stator winding schemes have also been compared, demonstrating the efficiency of copper utilization in toroidal windings. The electromagnetic calculus of the axial machine has particularities compared to the cylindrical machine, in the paper is presented the method of correlating the geometry of the cylindrical and axial machines. In this case the method and recommendations used in the design of such machines may be used.

1. Introduction
Electromechanical converters - electric cars are increasingly being implemented in terrestrial and air transportation.

An attempt is made in the paper to develop an electromechanical converter designed to drive an electric or hybrid vehicle. The purpose of the research is to analyze several constructive schemes capable of efficiently achieving the electric drive of the vehicle. From the start the analysis of the converters was oriented towards the research of the machines with axial magnetic flux, excluding the classic machine with cylindrical construction.

The construction of two-rotor electromechanical converters eliminates one of their main drawbacks by compensating the axial forces of interaction between the stator and the rotors. These electric machines can be made with one winding on the stator package or with two independent flat windings.

As a result of the analysis, an experimental sample was made with cast aluminum rotor windings. In this construction, additional elements were introduced to save the electrotechnical steel and evenly distribute the magnetic induction from the air gap and the stator yokes. Analytical correlations have been established between the basic geometric dimensions of the axial and cylindrical machine.

2. Electromechanical converters of various executions
Electricity is the most efficient and convenient form of energy for transport and use. The basic element in this energy transformation process is the electric machine, capable of functioning as a generator or motor.

The accelerated development of new electrical device manufacturing technologies has also influenced parameters improvement, reduced active and constructive materials, and the appearance of the electric machine [1].
The use of computing in the design of electrical machines makes it possible to achieve a wide range of the most diverse constructions.

Electric cars are used more and more frequently as a personal electric transport. In this context, specific construction electric machines can be used to function as generator and motor [2], [3].

One of these types of constructions could be an alternating current electric motor with axial flux synchronous or asynchronous, with one or two rotors.

Figure 1 shows the synchronous electromechanical converter with an excited rotor by permanent magnets, and Figure 2 shows the asynchronous electromechanical converter with a rotor and a short-circuited winding. These converters were developed and realized within the Electromechanical Department of the Technical University of Moldova.

![Figure 1. Synchronous axial machine with a permanent magnet rotor](image1)

![Figure 2. Electromechanical asynchronous converter with a rotor](image2)

The stator winding in both cases is flat and the consumption of copper is considerable (Figure 3a). To reduce the amount of copper in axial flow electric machines, it is mounted on the toroidal winding stator (Figure 3b). In this case, it is efficient to use two rotors that are placed on both sides of the stator. The rotors are driven by the rotating magnetic field produced by the three-phase currents, which are closed through the toroidal stator winding.

![Figure 3. Stator axial construction packages with diverse types of windings: a) Flat winding; b) Toroidal wrapping](image3)

The large radial and small axial dimensions of the axial converter allow for a large number of poles and low angular velocity.
The priority of the two-rotor axial machine and toroidal winding consists in the possibility of changing the number of poles because the opening of the winding section does not depend on the polar step as in the case of the winding in machine of the cylindrical construction. Thus, the toroidal winding gives the possibility to realize an axial multi-speed asynchronous converter, using a single winding. This could exclude the gearbox of the vehicle by using an electric switch.

It is then proposed to construct a two-rotor three-phase asynchronous machine (Figure 4). The stator has two packages with rings and mounted on the shaft. This device together with the rotors is mounted by means of the bearings on the shafts. The shafts provide rotation of the rotors in the same direction or in different directions. In the notches of the stator packages are mounted two three-phase windings, these having $2p_1 = 2p_2$ or a number of different poles $2p_1 \neq 2p_2$. The rotor windings are short-circuited and cast from aluminum in notches or cast and further mounted in the notches of the rotor package if it has open notches, which is an advantage of this technology.

![Figure 4. Electromechanical converter with flat stator windings and short-circuited rotor windings](image)

Such a construction of the axial asynchronous machine has certain advantages compared to the cylindrical construction electric machine, being used in motor or generator modes. Firstly, the construction consists of two machines in a single block, these ensuring the reduction of the active and constructive material used in the production. Another advantage is that the machine can operate simultaneously in the motor and generator mode, thus ensuring battery charging and vehicle operation.

The proposed asynchronous machine replaces the differential in vehicle construction because each of the two stator windings can be fed at different frequencies, so the rotors can rotate at different angular speeds.

In the construction of the two-rotor axial machine, the magnetic induction in the air gap and the stator and rotor yokes are distributed unevenly (Figures 5 a, b). For uniform distribution of magnetic induction, the heights of hooks $h_1$ and $h_2$ are different. Thus, the electrotechnical steel is efficiently used and the magnetic induction curve of the air gap near the sinusoid is obtained. The design of the proposed asynchronous machine has reduced axial dimensions and the cooling surface of the rotors is open, therefore the current density in windings can be increased by (1.3-1.5) times.

In order to ensure the operation of the asynchronous machine in generator mode the capacitors are provided in the winding schemes [4], [5].
3. Correlation between the basic dimensions of cylindrical electric machines and electric machines with axial flux

In the cylindrical asynchronous machine, the magnetic induction in the tooth area is not evenly distributed.

In order to adapt the design methods of axial asynchronous machines to the design of cylindrical electric machines, further attempts are made to analytically establish correlations between the sizes and basic dimensions of these electric machines [6], [7].

Traditionally, it has been found that the basic geometric dimensions of conventional cylindrical electrical construction machines are diameter $D$ and length $l_s$, determined by the type of machine.

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**Figure 5.** Magnetic induction curve distribution in the rotor yoke:

a) The curves of the magnetic induction variation in the rotor yoke along the polar step;

b) The curve of the magnetic induction variation in the rotor yoke in the radial direction.
respectively. For synchronous, synchronous and asynchronous AC motors, \( D \) is the internal diameter of the stator, and for DC machines \( D \) equals the outer diameter of the rotor.

By accepting that some parameters of the electric machine, such as the winding factor \( K_{W1} \) and the coefficient of form of the \( K_B \) electric motor, have values close to the unit, the expression for the constant of the electric machine can be written as follows:

\[
\frac{D^2 \cdot l_\delta \cdot \Omega}{P_c} = \frac{1}{\alpha_\delta \cdot A \cdot B_\delta}
\]

(1)

Where: \( P_c \) – the calculated power of the cylindrical construction machine, \( A \) – linear load of current and, \( B_\delta \) – magnetic induction in the air gap.

Considering that the shape of the magnetic curve can be considered as sinusoidal, the polar coverage coefficient:

\[
\alpha_\delta = \frac{2}{\pi}
\]

And the expression (1) is immediately as following:

\[
\frac{D^2 \cdot l_\delta \cdot \Omega}{P_c} = \frac{\pi}{2 \cdot A \cdot B_\delta} \Rightarrow P_c = \frac{2 \cdot D^2 \cdot l_\delta \cdot \Omega \cdot A \cdot B_\delta}{\pi}
\]

(2)

In the design of electric machines, regardless of machine construction, calculation methods are used based on the constant of the electric machine, which takes into consideration the power, geometric dimensions and electromagnetic stresses of the projected machine.

From a physical point of view, the constant of the electric machine expresses what power can be obtained from the volume of the active mass of the electric machine at a certain angular velocity \( \Omega \). This condition must also be observed for other constructions of electrical machines, such as, for example, the asynchronous machine with axial flux [8].

Figure 6 shows the basic geometric dimensions of the axial electric machine.

![Figure 6. The basic dimensions of the stator packet](image-url)
In this case the average force on a surface unit $F_S$ acting on the side surfaces of the cylinder is given by the expression

$$F_S = \alpha \cdot B_{sm} \cdot A_m$$  \hspace{1cm} (3)$$

Where: $B_{sm}$ – is the mean value in the axial machine air gap, $A_m$ – is the linear load of current corresponding to the mean diameter $D_m$.

The electromagnetic torque is determined with the expression:

$$M = \frac{1}{2} \cdot \frac{D_E + D_l}{2} \cdot 2S_L \cdot F_S$$  \hspace{1cm} (4)$$

Where the side surface of the active part:

$$S = \pi \cdot \frac{D_E^2}{4} - \pi \cdot \frac{D_l^2}{4} = \frac{\pi}{4} \left(D_E^2 - D_l^2\right)$$  \hspace{1cm} (5)$$

Substituting (3) and (5) into (4) we obtain:

$$M = \frac{1}{2} \cdot \frac{D_E + D_l}{2} \cdot \frac{\pi}{2} \left(D_E^2 - D_l^2\right) \cdot \alpha \cdot B_{sm} \cdot A_m$$  \hspace{1cm} (6)$$

or

$$M = D_m^2 \cdot l \cdot B_{sm} \cdot A_m$$  \hspace{1cm} (7)$$

where

$$D_m = \frac{D_E + D_l}{2}, \quad \frac{(D_E - D_l)}{2} = l$$

The left and right sides of the expression (7) multiply at the angular velocity, so we get:

$$\Omega \cdot M = D_m^2 \cdot l \cdot B_{sm} \cdot A_m \cdot \Omega$$  \hspace{1cm} (8)$$

Or the axial machine’s calculated power

$$P_a = D_m^2 \cdot l \cdot B_{sm} \cdot A_m \cdot \Omega$$  \hspace{1cm} (9)$$

The expression (9) can be written like follows:

$$\frac{D_m^2 \cdot l \cdot \Omega}{P_a} = \frac{1}{B_{sm} \cdot A_m} = C_A$$  \hspace{1cm} (10)$$

Then the formula for the constant of the electric machine of axial construction is the same, only that the basic geometric dimensions $D_m^2$ and $l$ do not express the real volume of the active part. The equivalent volume of the active part of the axial machine (Figure 5) can be given with the product: $D_m^2 \cdot l$, where $l$ is the radial cylinder length of the axial flux machine.

In order to obtain the same power from the same volume of active material for both cases, it is necessary:

$$P_c = P_a$$  \hspace{1cm} (11)$$

According to (2), these powers are different $\frac{2}{\pi}$ times, but the length of the axial machine package is less than the calculus length of the cylindrical machine $l_\delta$ about 0.7 times (Figure 6). The advantage of the axial machine is opportunity to save the active material.
In Figure 7, a and b are given graphs of variation \( l = f(P_a) \) and \( l_\delta = f(P_c) \) for different angular velocities (\( \Omega \)).

![Graph of variation](image)

**Figure 7.** The variation graphs of \( l = f(P_a) \) and \( l_\delta = f(P_c) \)

In Figure 8, a and b show the variation graphs for \( D_m = f(P_a) \) and \( D = f(P_c) \) for various axial and cylindrical machines.

![Graph of variation](image)

**Figure 8.** The variation graphs for \( D_m = f(P_a) \) and \( D = f(P_c) \)

Knowing the correlations between the cylindrical and axial machine diameters, the cylindrical machine recommendations can be used to design the axial machine. Therefore, the calculation power for the asynchronous axial flux machine can be calculated with the following expression:

\[
P'_a = \frac{k_E P_n}{\eta_n \cos\phi_n}
\]

The coefficient of the electric motor \( k_E \), the \( n_n \) and \( \cos\phi_n \) yields in the first approximation can be considered as sizes corresponding to the cylindrical machine and the axial magnetic flux machine. Calculated length of magnetic air gap in radial direction:

\[
l = \frac{P'}{\alpha_\delta \cdot k_{n1} \cdot A \cdot B_\delta \cdot D_m^2 \cdot \Omega}
\]

The outer and inner diameters of the stator packet (Figure 7) are determined, respectively, by the following relations:
\[ D_e = D_m + l; \]
\[ D_f = D_m - l. \] 

These diameters describe circles that comprise the actual active surfaces of the axial machine.

4. Conclusions

✓ Electric motors are used more and more frequently in personal electric transport.
✓ Electric axial construction machines have advantages over the cylindrical ones in terms of their use in traction on electric or hybrid vehicles.
✓ The proposed three-phase asynchronous machine has less weight and lower cost compared to other types of electric machines.
✓ The magnetic induction curve in the air gap is obtained close to the sinusoid by using yokes with different height.

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