

High-performance flux-switching DC motors for energy facilities

A D Golykov¹, S P Gladyshev¹ and A N Gorozhankin²

¹ Michigan-Dearborn University, Detroit, United States

² South Ural State University, Chelyabinsk, Russia

E-mail: DetroitUniver@gmail.com

Abstract. An overview of flux-switching DC Motor, which received an impetus to development due to progress in the field of information and power electronics, is given. The relevance of the optimization procedures that would allow to determine the best ratios of the elements of the magnetic system in terms of increasing the specific torque in each dimension is shown. Based on the ratios of elements of the magnetic system obtained using a finite element analysis, fragments of the electromagnetic calculation technique of a machine are given. According to the proposed method of calculation, an electric machine with a power of 18 kW was designed. It is shown that the specific torque and its pulsations in the studied electric machine are close to those of an asynchronous machine with a squirrel-cage rotor of the same size. At the same time, it is superior to the asynchronous machine in terms of its adjustment characteristics, overload capacity, speed control range, and manufacturability. The field of application of such an electric machine is mechanisms with a large range of speed control, large overload torques and high requirements for specific indicators of torque and power. An example of such a mechanism is electric and hybrid transport.

1. Introduction

Flux-switching DC Motor (FSDC) belong to a class of machines that contain two independent physically separated windings on the stator [1]. The first of these is the excitation winding, and the second is the armature winding. Electromechanical conversion in such machines is only possible due to the magnetic non-symmetry of the rotor, which does not contain windings. Such electric machines are characterized by high specific torque, good overload capacity, large speed control range, manufacturability and low manufacturing cost [2, 3]. There are three subclasses of machines: with electromagnetic excitation [4], with excitation from permanent magnets [5] and combined excitation [6]. The advantages of the first limiting variant with an electromagnetic excitation winding are: a large range of speed control, including in the second quadrant, high overload capacity, manufacturability and low manufacturing cost. The disadvantage is the low specific torque relative to the variant with excitation from permanent magnets [7]. The advantage of the second limiting variant with excitation from permanent magnets is a high specific torque. Disadvantages – the difficulty of weakening the field, the high cost of permanent magnets, their temperature instability, the possibility of demagnetization [8]. The hybrid variant is located between the two marginal subclasses described. From this we can conclude that an increase in the torque of a machine with electromagnetic excitation, which is achieved by optimizing the geometry of an electric machine, is relevant [9].



The optimization here should go according to the criteria for increasing the ratio of specific torque and specific power to cost [10, 11], i.e. in absolute terms, such machines may not reach the heights of machines with permanent magnets, but in terms of their relative performance they must exceed.

2. Overview of FSDC

All possible topologies of electric machines of this class are determined from the ratio of the number of teeth on the stator N_S and the rotor N_R according to the following equation:

$$\begin{aligned} N_S &= 2 \cdot i \cdot m \\ N_R &= 2 \cdot i \cdot m \pm 2 \cdot j \end{aligned} \quad (1)$$

The basic three-phase topology is formed by substituting the values $i = j = 2$ into equation (1). It turns out $N_S = 12$ and $N_R = 8$ (the minus sign is taken before the second term).

The term “magnetic flux switching” [12] reflects the principle of operation of the machine (Figure 1). The dark color shows the excitation winding, and the light winding of the armature. In the excitation winding current does not change. In the armature winding, the current changes. A total of three options are possible for switching on the armature windings in pairs 2–3– (Figure 1a), 1+2+ (Figure 1b) and 1–3+ (Figure 1c). The first phase winding of the armature occupies a position with a vertical magnetic axis, the second is shifted clockwise by 60° , the third is shifted by 120° also clockwise relative to the first. The positive direction of the current in the phase is considered such when the current is directed to us in the turns to the left of the magnetic axis of the winding and from us in the turns to the right windings. For example, in figure 1a the current in the second phase winding is negative, since to the left of the magnetic axis, the current is directed from us, and to the right – to us. The rotor teeth are numbered for ease of perception of its rotation. The arrows at the numbers of teeth indicate the direction of the force applied to the tooth. So, at a time, the rotor turns at an angle of 15 mechanical degrees. During the period of current change in the armature winding of the rotor is rotated by 45 mechanical degrees.

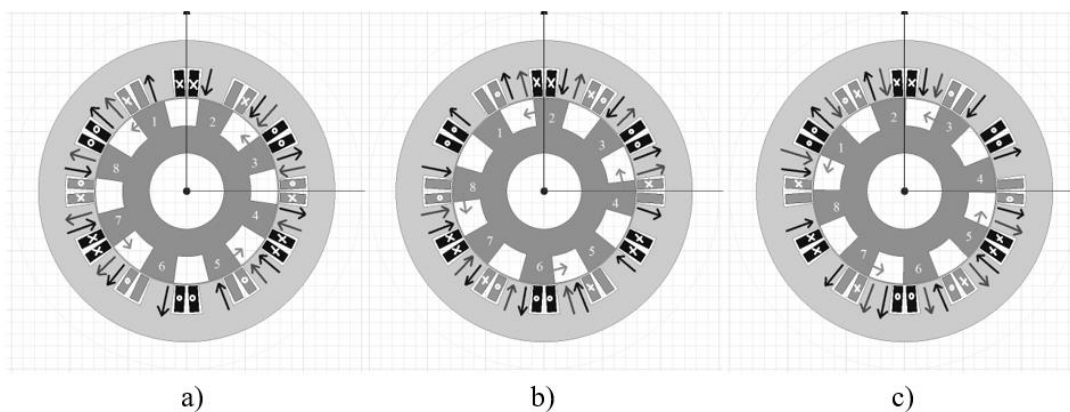


Figure 1. The principle of the electric machine’s operation.

3. Optimization of the elements’ ratio of the machine’s magnetic system

The elements of the magnetic system of the machine are: the teeth of the stator and rotor, the back of the stator and rotor, the air gap.

The optimization parameters [13] are the characteristics of the elements of the magnetic system: the thickness of the stator’s back, h_{aS} , the thickness of the rotor’s back, h_{aR} , width b_{zS} and height of the teeth of the stator h_{zS} , width b_{zR} and height of the teeth of the rotor h_{zR} , air gap width δ .

Limitations are:

1. The outer diameter of the stator D_N for the thickness of the backs of the stator and rotor, the height of the stator and rotor slots, as well as the air gap,

2. The size of the teeth division for the width of the teeth of the stator and rotor.

The optimization criterion is torque T .

The stator and rotor teeth are magnetically identical [14]. With a large difference in the width of the teeth, the magnitude of the magnetic flux passing through the teeth will be determined by teeth of a smaller width, which will be saturated [15]. In this case, a change in the magnetic energy as a function of the angle of rotation of the rotor will occur with a speed determined mainly by wide teeth [16]. This will lead to a decrease in the average torque for the period of change of magnetic energy, since a small tooth, when moving under (above) a large tooth, does not change the energy of the magnetic field. In the case of identical teeth of small width, the maximum value of magnetic energy will be small, and its change as a function of the angle of rotation of the rotor will occur in a short period of time [17]. In this case there will be a short-term ejection of the torque with its subsequent establishment in the region of zero value. We get unacceptable torque ripple when the machine is running [18]. In the case of identical large teeth, the minimum level of magnetic energy will tend to the maximum, and the torque will tend to zero [19].

Summarizing the arguments in all three cases, it can be argued that the width of the teeth should be enough to minimize the torque pulsations on the one hand and to achieve the maximum difference in magnetic energy in a consistent and mismatched position of the teeth on the other. The width of the teeth of the stator and the rotor should be approximately the same.

To simulate the machine under study, let us set the basic parameters of the magnetic system ($h_{as} = 20$ mm, $h_{ar} = 23$ mm, $b_{zs} = 21$ mm, $h_{zs} = 28$ mm, $b_{zr} = 31$ mm, $h_{zr} = 23$ mm, $\delta = 0,5$ mm, $d_B = 64$ mm). Electromagnetic loads choose the same as that of the asynchronous prototype machine (linear load $A = 20600$ A/m, current density in the windings $J = 5$ A/mm²).

To test the assumptions on the choice of the width of the teeth in the simulation will change the width of the teeth of the rotor (Figure 2). With narrow rotor teeth, the width of which was $1/3$ of the pole division (Figure 2, curve 1), the mean value of the torque was $T = 90$ N·m, and its ripple was 55% [20]. With an average width of the rotor teeth, which was $1/2$ of the pole division (Figure 2, curve 2), the mean value of the torque was $T = 95$ N·m, and its pulsations were 25% [21]. With a rotor teeth width of $2/3$ pole division (Figure 2, curve 3), the mean value of the torque was $T = 80$ N·m, and its ripple was 35% [22]. The best was the average option width of teeth.

The width of the stator teeth did not vary, since this changes the area of the grooves to accommodate the winding conductors, and this leads to a change in the linear load and current density. These parameters were kept constant during simulation for correct comparison of machines by specific torque.

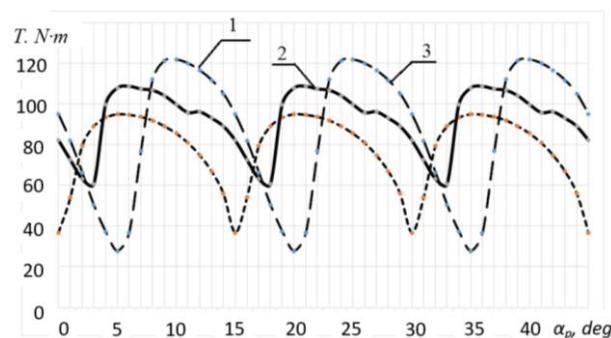


Figure 2. The torque characteristics for different widths of the rotor teeth: 1 – 0.33 from the pole division; 2 – 0.5 of pole division; 3 – 0.66 of pole division.

The search for the optimum height of the rotor teeth was carried out by varying this size by increasing the back of the rotor and fixing the maximum torque on the angular characteristic [23, 24].

According to the simulation results, when the height of the teeth decreases, there is no noticeable change in the torque [25]. This can be explained by the sufficient depth of the groove for the

concentration of the magnetic field in the teeth. In our case, the magnitude of the rotor tooth [26, 27] in 20 values of air gaps $h_{zR} = 20\delta$ is sufficient. Increasing the back of the rotor does not increase the torque due to the saturation of other elements of the magnetic system [28]. A further increase in the height of the teeth does not give an increase in the torque [29]. The sharp decrease in the torque when the height of the teeth tends to zero is explained by the penetration of the buckling fields into the interpolar gap and the creation of an inhibitory torque up to the setting of the resulting force to zero.

The value of the maximum value of the torque on the angular characteristic as a function of the size of the stator and the rotor backs in fractions of the width of the stator teeth is shown in [30, 31]. The idea of simultaneously reducing or increasing the width of the stator and the rotor backs is explained by the fact that the same magnetic flux passes through these backs and they are equally saturated. If you increase one of the backs, the second will go out in saturation and the torque will not increase. Reducing one of the backs will also lead to its saturation. The obtained characteristic resembles a magnetization curve, where saturation occurs approximately from the width of the backs to 30% of the width of the stator teeth, while the torque continues to grow, but at a much lower rate. It is proposed to search for the optimum here by holding a straight-line coinciding with the left side of the characteristic [32, 33]. The presence of a mismatch region indicates an increase in the rate of reduction of the torque. The optimal size of the backs is equal to the width of the teeth of the stator $h_{aS} = h_{aR} = h_a = b_{zS}$.

Based on the obtained optimal ratios of the magnetic system's elements of an electromechanical converter, a method of electromagnetic calculation can be obtained.

4. Fragments of the electromagnetic calculation method of an electric machine

The diameter of the rotor and the length of the package we define for the required torque according to the equation [34, 35]:

$$M = K \cdot D_r^2 \cdot L_s \quad (2)$$

where D_r is the diameter of the rotor; L_s is the stator packet length; K – proportionality coefficient, which lies in the range from 20 to 35 kN·m/m³.

Instead of calculations by the equation (2), you can take the dimensions of an asynchronous machine that would provide the required torque and rely on its parameters.

All the elements of the magnetic system of the machine will be interconnected based on their optimal ratios and coordination of the required value of the MDS to create the magnetic flux of the desired size and the capabilities of the machine in terms of the winding location and restrictions on the current density in it.

The required or desired MDS in the groove is determined from the equation:

$$F_p = k_s \cdot \frac{1}{\mu_0} \cdot B_\delta \cdot \delta \quad (3)$$

where k_s is the saturation coefficient (lies in the range 1.2 ... 1.4); $\mu_0 = 4\pi \cdot 10^{-7}$ GN/m is the magnetic permeability of the air gap; B_δ – induction above the teeth in the coordinated position (lies in the range of 1.8 ... 2 T); δ – the size of the air gap.

On the other hand, the MDS groove is determined by its area, current density and the fill factor of the groove with copper:

$$F_p = k_M \cdot S_p \cdot J \quad (4)$$

where k_M – the fill factor of the groove with copper (lies in the range of 0.4 ... 0.8); J is the current density in the winding (approximately 5 A/mm²); S_p is the groove area.

From equations (3) and (4) determine the desired groove area:

$$S_p = \frac{k_s \cdot B_\delta \cdot \delta}{k_M \cdot J \cdot \mu_0} \quad (5)$$

Then we need to establish on what parameters of the magnetic system depends the area of the groove and how these parameters interrelate with each other.

The outer diameter of the stator of the machine is fixed and is determined from the relationship:

$$D_H = d_B + 2 \cdot h_{aR} + 2 \cdot h_{zR} + 2 \cdot \delta + 2 \cdot h_{zS} + 2 \cdot h_{aS} \quad (6)$$

where d_B is the diameter of the machine shaft; h_{aR} – width of the back of the rotor; h_{zR} – the height of the rotor's teeth; h_{zS} is the height of the stator teeth; h_{aS} is the width of the backrest of the stator.

According to optimization results $h_{aS} = h_{aR} = h_a = b_{zS}$, a $h_{zR} = 20 \cdot \delta$.

The width of the stator tooth is determined from the equation:

$$b_{zS} = 1,1 \cdot \frac{\pi \cdot D}{N_s} \cdot \tau \quad (7)$$

where τ is the width of the stator tooth in relation to the tooth division; D is the inner diameter of the stator bore; the coefficient of 1.1 is taken to obtain the average tooth width in height, and not its minimum width near the air gap.

The inner diameter of the stator bore is determined by the sum of the elements of the rotor magnetic system:

$$D = d_B + 2 \cdot h_{aR} + 2 \cdot h_{zR} + 2 \cdot \delta = d_B + 2,2 \cdot \frac{\pi \cdot D}{N_s} \cdot \tau + 42 \cdot \delta \quad (8)$$

5. Fragments of the electromagnetic calculation method of an electric machine

According to the given parameters, the elemental models of the machines are compiled in the Ansys Maxwell software package. The results of the calculation of the torque as a function of the angle of the rotor's rotation are presented in Figure 3. The average torque of both machines is approximately the same and was as follows for the asynchronous machine $T_{AM} = 119 \text{ N}\cdot\text{m}$, and for the machine under investigation $T_{FSDC} = 121 \text{ N}\cdot\text{m}$. The size of the pulsations, both machines were also almost the same. this figure was 22% for an asynchronous machine, and 25% for a synchronous machine with switching of the magnetic flux and excitation winding on the stator. It should also be noted that the frequency of the pulsations of the asynchronous machine's torque is much higher. This is due to the large number of teeth on the "smooth" stator and the jagged harmonics of the torque. The pulsations of the torque of the machine under observation are explained by a decrease in the intensity of the change in the magnetic energy in the system before switching the current in one of the windings of the machine armature.

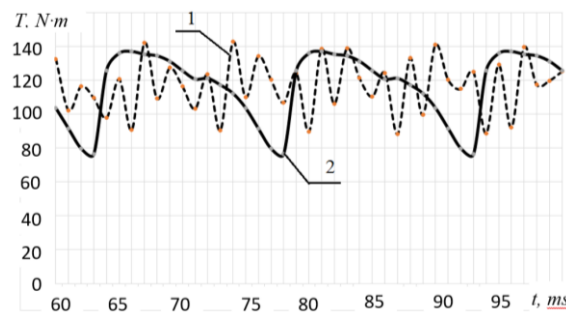


Figure 3. Curves of the torque as a function of time for two electric machines: 1 – asynchronous machine MO160M4; 2 – Flux-switching DC Motor.

6. Conclusion

According to the results of the study, the following conclusions can be drawn:

1. A method is proposed for optimizing the elements of the magnetic system of a machine based on the principle of splitting the machine geometry into elements that independently influence the optimization criterion (width of the rotor teeth, width of the backs, depth of the rotor slots). The result of optimization using finite element analysis is the ratios of the magnetic system's elements of the machine ($h_{aS} = h_{aR} = h_a = b_{zS}$ и $h_{zR} = 20\delta$). In addition, this technique is applicable to other topologies of synchronous electromechanical converters with switching of the magnetic flux and excitation winding on the stator;

2. Considering the optimal ratio of the magnetic system's elements of the machine, fragments of the electromagnetic calculation technique are proposed. The idea of the technique is to find the size of the slots on the stator to accommodate the windings, which would provide the desired value of MDS for the machine to operate at the nominal point close to saturation. Change the size of the grooves by changing the width of the teeth of the stator. In the optimization example, the width of the teeth has not changed;

3. According to the results of the comparison, the machine under investigation is comparable in terms of specific torque and its pulsations to an asynchronous machine of the same size.

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