Electric drive of the generator of the diesel-electric tractor DET-250M2 on the basis of a Field Regulated Reluctance Machine

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Abstract. The diesel electric tractor DET-250M2 was the first tractor in the USSR with an all-electric transmission. This tractor usually works in agriculture as a cultivator and a bulldozer. However, it is often used in the railway sector, in industry, in large construction projects. Since the tractor’s electrical installation developed in the 1950s on the basis of DC collector machines is now obsolete, difficult to maintain, it was decided to upgrade the traction electric drive. The article presents the calculations of an electric machine: optimization of the rotor geometry, selection of the optimal ratio of the pole and interpolar gap, selection of the optimal number of poles of the machine, selection of the current shape, type of rotor. As an electric machine, a FRRM, which characterized by high overload capacity, a wide range of work in terms of torque and speed, was selected.

1. Introduction

Electric traction allows you to provide the highest starting torque, which for the tractor is perhaps one of the main indicators. Quiet operation allows the driver to work in comfortable conditions.

Development of a set of electric traction drive for the tractor DET-250M2 was performed by specialists of the Chelyabinsk company LLC Scientific and Technical center "Drive technology” under an agreement with LLC "CHTZ-URALTRAK».

2. Technical characteristics of the tractor's electrical installation

The tractor electrical installation kit includes: a generator, electric motors that independently drive each of the wheels of the rear wheelset, an electric drive control unit, an on-board power converter 24 V.

This article is devoted to the design of an electric generator machine [1].

Power Converter BS-20P is designed to control electric machines of the tractor. The power Converter provides power to two ID-110 traction motors with a power of 110 kW from the IG-225 generator with a power of 225 kW, as well as battery charging and power to consumers of the low-voltage onboard network [2]. The BS-20P unit provides processing of tractor control signals and output of diagnostic information to the graphical panel in the tractor cab [3].

The converter provides the following modes of operation [4]:

• transport mode;
• operating mode;
• braking mode at zero speed;
• holding the set speed during descent and ascent on slopes.
• In transport and operating mode, the converter provides [5]:
• full use of free diesel power with an error of no more than 3%;
• smooth change of speed and reversal of the direction of movement of the traction motor shaft;
• turn in motion and turn the tractor in place by setting different speeds on the right and left traction motors [6].

Table 1 shows the catalog data of the electric machine used as a generator.

| Table 1. The catalog data of the electric machine. |
|-----------------------------------------------|
| Rated power  $P_n = 240$ kW                  |
| Rated speed  $n_a = 430$ rpm                 |
| Maximum speed  $n_{max} = 2250$ rpm         |
| Number of poles  $2p = 6$                    |
| External diameter of the stator package  $D_a = 650$ mm |
| The inner diameter of the bore  $D = 490$ mm |
| The length of the stator package  $l_{delta} = 800$ mm |
| The number of stator slots  $Z = 72$        |
| The number of parallel branches  $a = 6$    |
| Rated phase voltage  $U_f = 380$ B          |
| Rated stator current  $I_a = 210$ A         |
| The number of effective conductors in the groove  $u_p = 28$ |
| The number of turns in phase  $w_f = 28$    |
| Current density in the winding  $J = 4.1$ A/mm$^2$ |
| Number of elementary conductors  $n_{el} = 2$ |
| Wire mark  PSD rectangular wire  |
| Dimensions  1.12 mm x 4 mm,  |
| conductor cross section 4.265 mm$^2$        |

3. Technical characteristics of the tractor’s electrical installation

The generator of the diesel-electric drive of the tractor has high requirements for overload capacity (short-term), stability of the output voltage. For this reason, synchronous machines are usually used as generators [7]. It is customary to distinguish reactive machines in a separate class, in which the electromagnetic moment is created due to the reactive component of the moment. The rotor design does not contain a winding [8]. The excitation in the machine is created by currents in the grooves located in the interpolar spaces [9]. The contour of the flow lines passes through a pair of poles and a part of the stator located between them. The interaction of this flow with the current flowing in the grooves located above the rotor poles creates an electromagnetic moment [10].

Based on the principle of the formation of phase currents, we can distinguish subtypes of the control system [11]. So, in the case where the switching of currents occurs as a function of the position of the rotor, independently in each winding, we can talk about independent control over the excitation channel. In other words, any winding at any given time can fulfill both the functions of creating the excitation of the machine and the function of generating the electromagnetic moment [12]. Physically, this is realized by connecting each winding to a current source, the level and shape of which is determined by the controller of the control system [13].

This machine, known in the literature as a Field Regulated Reluctance Machine FRRM, is used as a traction motor and generator of the diesel electric tractor DET-250M2 [14].
4. Designing an electrical machine
Optimization of the parameters of the electric machine for its further use as FRRM, included the following steps [15]:

- Selecting the optimal number of pairs of machine poles [16];
- Selection of the optimal height of the stator back (the ratio of the rotor diameter to the stator diameter Dc/DC) [17];
- Selection of the optimal ratio of the magnetic conducting part of the rotor (pole α) to the magnetic non-conducting part (interpolar gap β), clearly shown in figure 1;
- Selection of the rotor type [18].

![Figure 1. The ratio of the pole arc α to the pole β.](image)

The optimization criteria were: the maximum value of the generated torque, the minimum value of the amplitude of the pulsations of the moment, due to both gear and switching pulsations [19].

The restrictions were: the dimensions of the machine, the admissible values of induction in the air gap and back of the stator, the maximum rms current, the excess of which is unacceptable from the conditions of heating the machine [20].

This multicriteria optimization was carried out sequentially in the order indicated above [21].

The calculations were carried out on a model with distributed parameters by the finite element method in the Ansys APDL software package [22]. FRRM with the required power was taken as the initial version. The grade of steel used is 2213 [23]. The calculation was carried out with an iterative accuracy of 0.8%. Higher convergence of the calculation required a significant increase in the calculation time or the amount of resources used. The calculation was carried out in a plane-parallel formulation of the problem [24]. The slope of the grooves was taken into account indirectly, according to the average calculation indicators in the middle of the machine and two ends. The type of calculation is magnetostatic, each point represents a static calculation of the magnetic field pattern [25].

These indicators were fixed on the angular characteristics—the dependence of the electromagnetic moment created by the electric machine on the angle of rotation of the rotor. Secondary indicators (induction, current) were recorded separately for each calculation [26].

Figure 2 shows the key points of optimization - the angular characteristics of the initial version, the optimal ratio of the pole to the interpolar gap α / β = 0.4; the key points of the ratio of the diameter of the rotor to the diameter of the stator 0.7 and 0.72. Table 2 also shows selectively the most characteristic points located in the vicinity of the optimal option [27].
Optimization of the number of pole pairs allowed us to achieve the optimal linear load of the machine. With a large number of poles, the cost of the converter increases, since in accordance with the Kotelnikov theorem [28], for the formation of the transmitted signal, a carrier frequency of at least two times the frequency of the transmitted signal is required. An increase in the number of pole pairs will require the formation of the required currents to increase the carrier frequency of the converter over 16 kHz [29].

Optimization of the ratio of the diameters of the stator and rotor made it possible to achieve the optimal electromagnetic loading of the stator back: all the material is penetrated by flow lines, but the induction does not exceed the permissible norm [30].

Optimizing the pole to interpolar gap ratio helps minimize magnetic losses. Too narrow a pole would lead to dispersion fields and spurious forces [31]. Too wide a pole would not allow to obtain the maximum electromagnetic moment [32]. It should be noted separately that the use of a “cold” rotor, without winding, makes it possible under the heating conditions to increase the linear load compared to a synchronous motor, since the conditions for heat removal in the stator are better [33].

Table 2. Results of the optimization of the stator.

| 2p | \(D_r/D_s\) | \(\alpha/\beta\) | \(B\) in the time, \(T_l\) | \(B\) in the back, \(T_l\) | \(M_{mid}\) | A ripple | A ripple/ \(M_{mid}\) | \(I\), A (into the groove) |
|-----|------------|----------------|--------------------------|--------------------------|----------|----------|-------------------|--------------------------|
| 6   | 0.75       | 0.5           | 1.8                      | 1.3                      | 4.21     | 4.7       | 1.1               | 980                      |
| 6   | 0.7        | 0.5           | 1.9                      | 1.3                      | 4.28     | 3.6       | 0.8               | 980                      |
| 6   | 0.72       | 0.4           | 1.9                      | 1.1                      | 4.56     | 4.3       | 0.9               | 980                      |
| 6   | 0.7        | 0.4           | 1.9                      | 1.2                      | 6        | 5.76      | 0.96              | 980                      |
| 4   | 0.6        | 0.5           | 1.9                      | 1                        | 3.7      | 2.5       | 0.7               | 800                      |
| 4   | 0.7        | 0.5           | 2                        | 1.8                      | 4.4      | 2.56      | 0.6               | 900                      |
| 4   | 0.7        | 0.4           | 2.2                      | 1.9                      | 4.8      | 2.4       | 0.5               | 900                      |
| 8   | 0.75       | 0.5           | 1.9                      | 1.6                      | 4.8      | 3.96      | 0.82              | 735                      |

Figure 2. Angular characteristics obtained on the model.
5. Selection of rotor type and current shape

Due to the fact that the design of the machine was carried out according to an individual project, it was important to take into account the moments associated with the subsequent production of these machines and the choice of converters for them. So, the standard explicit pole rotor shown in figure 1 can be made monolithic [34]. This greatly simplifies the technology of its manufacture. But in this case, the problem of eddy currents arises, which in a machine of such power will lead to significant losses [35].

The solution to the problem is the transition to a lined rotor. Among other advantages, this option opens up new possibilities for manufacturing a complex rotor [36]. Figure 3 shows the rotor of FRRM with magnetically non-conductive inserts. The principle of operation of the machine, provided that this rotor is used, is similar to that described above [37]. The stator windings located above the longitudinal axis of the magnetic circuit d create an electromagnetic field, excitation in the electric machine. The interaction of the created field with the current in the grooves located above the magnetically non-conducting part (transverse component, q axis) creates an electromagnetic moment [38].

![Figure 3. Rotor of FRRM with magnetic non-conducting inserts.](image)

The advantages of the given variant are minimization of dispersion fields, spurious fluxes. This was proved in the works of the American scientist A. Vagati. Since the burnt rotor is made from a set of disks obtained by the mold, the complication of the rotor geometry does not complicate its manufacturing technology [39].

Table 3 shows a comparison of the obtained RMS current with a simple rotor and with a rotor with magnetic non-conductive inserts (figure 3). This calculation was made using a dynamic model. Transient processes were calculated using the ANSYS Simplorer environment, where the control system model was performed. The finite element model of the engine was integrated into the control system and data was exchanged at each step of the calculation. In other words, each step of the time calculation required recalculation of the magnetic system of the electromechanical converter.

The independent formation of currents of each phase makes it possible to form a complex shape of the surface current (along the stator bore). So, at the final stage of optimization, a surface current shape was selected between a sinusoidal and rectangular current shape.
motors are produced at the Snezhinsky factory of special electric machines. Further improvements in semi-conductor technology make it possible to obtain a larger amount of computing resources. The results of optimization are the ratio of the diameter of the rotor to the diameter of the stator equal to 0.72; the ratio of the pole to the pole gap, equal to 0.4; the number of pole pairs equal to 6, the use of conductive inserts, the formation of a rectangular current in the control system made it possible to obtain the maximum generated electromagnetic moment in the given machine dimensions. In this case, induction in the tines did not exceed the permissible limit of 1.9 T, in the stator back - 1.2 T. The amplitude of the pulsations in a fraction of the generated electromagnetic moment turned out to be quite high - 96%. Improvement of this indicator can be achieved by optimizing the value of the bevel of the grooves. In this work, it was not carried out. It is possible to qualitatively optimize the slanting of grooves on a model in a spatial formulation of the problem. This will also allow for the dispersion fields in the frontal parts of the winding. However, such a calculation requires an order of magnitude larger amount of computing resources.

It should be noted that the entire electrical installation obtained according to the design results was completed on components manufactured in Russia. Semiconductor technology is the company's own development (this article does not describe circuit solutions in the conversion technology), and electric motors are produced at the Snezhinsky factory of special electric machines.

**Table 3. Selection of rotor type and current shape.**

| Current shape | Simple rotor | Rotor with magnetically non-conductive inserts |
|---------------|--------------|-----------------------------------------------|
| Rectangular   | 36.8         | 34.9                                          |
| Sinusoidal    | 36.94        | 30.6                                          |

**6. Conclusion**

The results of optimization are the ratio of the diameter of the rotor to the diameter of the stator equal to 0.72; the ratio of the pole to the pole gap, equal to 0.4; the number of pole pairs equal to 6, the use of a rotor with magnetically non-conductive inserts, the formation of a rectangular current in the control system made it possible to obtain the maximum generated electromagnetic moment in the given machine dimensions. In this case, induction in the tines did not exceed the permissible limit of 1.9 T, in the stator back - 1.2 T. The amplitude of the pulsations in a fraction of the generated electromagnetic moment turned out to be quite high - 96%. Improvement of this indicator can be achieved by optimizing the value of the bevel of the grooves. In this work, it was not carried out. It is possible to qualitatively optimize the slanting of grooves on a model in a spatial formulation of the problem. This will also allow for the dispersion fields in the frontal parts of the winding. However, such a calculation requires an order of magnitude larger amount of computing resources.

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