Optimization of the magnetic system of a VR machine for traction electric drives in agriculture

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Abstract. The purpose of this article is to optimize a VR machine for traction electric drives in agriculture, as well as to identify its advantages and disadvantages, to compare an electric drive based on a test machine with an asynchronous electric drive of the same size. The optimal ratio of the elements of the magnetic system of the electromechanical converter based on the VR machine. It is shown that the overload capacity of an electric drive with a VR machine is about 25%. The specific electromagnetic moment of the studied machine is 30% higher than the corresponding indicator of an asynchronous machine of the same size in the nominal operating mode. The disadvantage of this machine is its low power factor, only 7%. This is due to the small ratio of conductivities along the longitudinal and transverse axes of the machine due to the large number of stator and rotor teeth. The problem is solved by introducing additional DC or AC windings on the stator. It is shown that a change in the air gap significantly affects the specific moment. Only by reducing by 2 times the air gap managed to increase the moment by 48%.

1. Introduction
In the last decade, permanent magnet synchronous motors on the rotor and electric drives based on them have replaced asynchronous electric drives for traction applications due to high specific torques, specific power and efficiency [1]. However, rare earth magnets are expensive and unstable in operation, so the development of machines without magnets has become more attractive. The disadvantage of such machines is a lower specific torque, however, they can be economically justified. Several machine topologies for traction applications have been developed [2]. This article discusses a VR machine without permanent magnets. The choice of the best sizes of the elements of the magnetic system significantly affects the specific performance of the machine, so optimization is relevant [3].

2. The statement of research problem
Despite the widespread use of induction motors, due to their cheapness and ease of maintenance, they have several disadvantages compared to other types of motors: low specific torque, low specific power and efficiency [4]. For this reason, in the past few decades, the induction motors have been replaced by permanent magnet motors, including permanent magnets not only on the stator, but also on the rotor. Electric drive with permanent magnet has a large specific moment, but they are expensive in production, which is a consequence of the increase in the price of permanent magnets [5]. Due to the high cost of electric drive with permanent magnet, there are tendencies for the development of machines without permanent magnets. One of the electric drive is working with this type of engine is the electric drive based on the VR machine, which this article is devoted to [6].
The possibility of using electric drives with this type of engine for electric cars is attractive because it eliminates the need to use a gearbox that needs to be serviced, in addition, it reduces the reliability of the system, increases its inertia, and complicates the operation scheme of electric vehicles [7].

Possessing a unique opportunity of low-speed high-torque work, such a machine has two drawbacks [8]. Firstly, due to the large difference in the speeds of the field and the rotor in the latter, large losses appear even without load [9]. This leads to a decrease in machine efficiency. Secondly, the reactive component of the armature current is usually large. This leads to a decrease in power factor to 0.2 ... 0.4 [10].

As mentioned above, the type of VR machine is most widely used and is of great interest for research [6]. There are a lot of additional tools and innovations for VR. In particular, types of VR with dual power supply (VRDF) have been actively studied recently [11], they have not been studied much, but they have great potential due to the high specific torque, which is achieved using an additional winding with alternating current on the stator (ACVR) [12] or DC windings also on the stator (DCVR) [13].

In addition, there are VR motors with elements of high-temperature superconductivity (HTS) [13], with a double stator [14], an external rotor [15], using zero sequence current in VRPM (permanent magnets) [16], using the VR design with a double slot on the stator [17].

The control system (CS) for this type of electric drive is similar to the control of an electric drive with a synchronous jet machine [18]. Frequency converters used to control other types of synchronous jet engines and asynchronous motors are compatible with VR motors [19]. In SU, it is absolutely necessary to use a rotor position sensor [20]. The possibility of using vector and DTC control during the transition from blood pressure to VR is also retained [21].

In connection with what was said in a scientific article, the following tasks were solved

- synthesis of a mathematical model of a VR machine [22];
- optimization of the geometry of the magnetic system of the VR machine [23];
- discussion of optimization results [24].

3. Synthesis of a mathematical model of a VR machine
As the initial data for the design, we took the data of an 18 kW induction motor. The idea is to create a model of an electric drive based on a VR machine in the dimensions of an asynchronous machine (AM) in order to compare them [25]. Thus, it will be possible to compare blood pressure and VR of the same size. In the [26] presents the initial data for creating a mathematical model of the studied machine [27].

The stator of the VR model is made in the likeness of the AM stator with the preservation of geometry [28]. In this work, we will study a model of an engine with 48 teeth on the stator and 52 teeth on the rotor [29]. If the number of teeth on the stator is greater than on the rotor, then the field and rotor rotate in different directions [30]. It is better that the stator teeth are smaller than the rotor teeth. This provides more space for stator winding [31].

The construction and solution of tasks was performed on the ANSYS Electronics Desktop platform, since this platform contains all the necessary modules for solving problems of this kind. In addition, using this platform, it is possible to build electrical (ECAD) and mechanical CAD (MCAD) geometric models [32]. The studies were performed using supercomputer resources at RikEnergo ltd. [33]. Work environment ANSYS Electronics Desktop is equipped with all necessary ANSYS calculation modules for solving electromagnetic problems [34]. Close integration between the modules provides unprecedented ease of configuration and use in solving complex design and optimization problems [35]. Thus, the construction and investigation of the VR machine will be performed in the Maxwell 2D module [36].

4. Optimization of the geometry of the magnetic system of a VR machine
We will consider the best geometry of this or that element such that the engine has the highest moment, since this type of engine has a large torque and the scope of its application is such that it is selected in the mechanisms and complexes that require the greatest moment [37].

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First of all, the width of the rotor grooves affects the moment of this engine. In its study, the initial value was chosen 2.1 mm, the pitch is 0.2 mm, changes were made to a value of 6.3 mm. Below are the results of a study of changes in the width of the grooves of the rotor at the time of the electric motor (figure 1). The best stator groove width was 4.2 mm at 190 Nm of torque.

![Figure 1](image1.png)

**Figure 1.** Change in torque depending on the width of the grooves of the rotor.

Also, the magnitude of the moment is affected by the depth of the grooves of the rotor, they have been modified and investigated in the same manner as described above. Below are the results of a study of changes in the depth of the grooves of the rotor at the time of the electric motor (figure 2). The distance from the axis of the machine to the bottom of the rotor groove is taken as the size of the depth of the rotor groove. And its meanings have changed and are described below.

![Figure 2](image2.png)

**Figure 2.** Change in torque depending on the depth of the grooves of the rotor.
Thus, the best geometry is 82.5 mm from the machine axis to the bottom of the rotor groove. Which is in good agreement with the results of other authors involved in VR electric machines [20]. The best result in the research conducted in this article is a rotor tooth depth of 4 mm. Thus, the difference in the ratio of the widths of the teeth of the rotor to the stator is 22%, which is an acceptable error, given the difference in the topologies of these VR machines, their dimensions, and capacities. We can conclude that despite the large difference in power and dimensions of VR machines, the greatest moment is achieved with approximately the same values of the depth of the grooves of the rotor.

In addition, the effect of the width of the stator teeth on the torque was investigated. Below are the results of the study of changes in the width of the stator teeth at the time of the engine (figure 3).

Thus, the ratio of the width of the grooves of the rotor to the stator is 4.2 / 6 (see figure 1). Which also agrees well with the results of other authors involved in VR electric machines [20]. The best result in the studies conducted in this article is the ratio of the width of the teeth of the rotor to the stator 4.4 / 5.4. Thus, the difference between the ratios of the width of the teeth of the rotor to the stator is 21%, which is an acceptable error, given the difference in the topologies of these VR machines, their dimensions, capacities.

![Figure 3. Change in torque depending on the width of the stator slots.](image)

5. Discussion of optimization results

After optimization, the dependence of the overload torque on the stator slot current was constructed. This study allows you to see exactly how the motor torque depends on the current supplied to the stator. The results are presented in figure 4. When the current increases above the nominal (552 A), the torque does not increase as intensely as to the nominal value. So with an increase in the stator current 4 times higher than the nominal value, you can get a moment 1.25 times higher than the nominal value.
Figure 4. Overload on model 52/48 with 1 mm and 0.5 mm clearance.

The overload graph shows that at a stator current of 552 A, the moment of motors with a gap of 0.5 mm and 1 mm differs by 48%, which indicates a more efficient use of a smaller gap (0.5 mm). Thus, we can conclude that the VR appearance of the machines is very sensitive to the size of the air gap [38].

The main integral values of the electric drive based on the VR of an electric machine are presented in table 1.

When comparing the obtained results of the VR model of the 52/48 tooth topology with the catalog BP data, we can see that the VR moment is 33% higher than the BP moment. The VR power factor is 7%, which is 92% less than the BP. From the results obtained, it can be concluded that the traction EP based on the VR machine is applicable, since according to the study, the goal of increasing the moment developed by the electric motor has been achieved. However, from these results it is confirmed that the VR engine has a low power factor (7%), which is a significant drawback of this type of engine when considering the energy efficiency of their application [39].

Table 1. Initial data for creating a model of a VR machine.

| Value                        | Designation | Value | Unit of change |
|------------------------------|-------------|-------|----------------|
| The average value of the     | \( M_{av} \) | 159.8 | N ⋅ m          |
| moment                       |             |       |                |
| The maximum value of the     | \( M_{max} \) | 170.4 | N ⋅ m          |
| moment                       |             |       |                |
The minimum value of the moment \( M_{\text{min}} \) is 145.4 N \( \cdot \) m.

The amplitude of the ripple moment \( A_r \) is 7.8%.

Effective value of current in phase A \( I_{\text{phaseA}} \) is 64.8 A.

Effective voltage value in phase A \( U_{\text{phaseA}} \) is 191.1 V.

Total power in phase A \( P_{\text{totalA}} \) is 12387.9 W.

Active power in phase A \( P_{\text{activeA}} \) is 860 W.

Power Factor in Phase A \( k_{\text{power}} \) is 0.07.

### 6. Conclusion

The following conclusions can be drawn as a result:

- As a result of the optimization of the magnetic system, the electromagnetic moment of the VR machine in the dimensions of the asynchronous machine turned out to be 33% higher than the moment of the last;
- VR power factor is only 7%. This is due to the small ratio of conductivities along the longitudinal and transverse axes of the machine due to the large number of stator and rotor teeth. The problem is solved by introducing additional DC or AC windings on the stator;
- It is shown that a change in the air gap significantly affects the specific moment. Only by reducing by 2 times the air gap managed to increase the moment by 48%.

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