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Features of Designing a Low-Speed Generator for the Accumulation of Gravitational Energy

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Abstract. The article is devoted to the study of increasing the efficiency of low-speed synchronous generators with permanent magnets as part of a system with a gravitational energy storage. Features analysis of the gravitational energy storage devices use was carried out. The shortcomings of pumped-storage power plants in comparison with solid-state storage power plants are considered. Practical significance: the research results were used in the development of low-speed generators with permanent magnets for use in a system with a gravitational energy storage. They can significantly reduce the weight and size of the system as a whole.

1 Introduction

At present, humanity is striving to reduce its harmful impact on the environment. Therefore, one of the main tasks of the energy industry is the introduction of environmentally friendly technologies for generating electricity.

The essence of clean energy is to reduce greenhouse gas emissions in the generation process, which requires the replacement of the traditional way of generating energy with alternative sources. Among the electric power plants operating at the expense of alternative energy sources (AES) are hydro turbines, wind turbines and solar panels.

Since AES cannot ensure the constancy of the generated power, for their application it is necessary to develop energy storage devices (ES) with a minimum cost and high efficiency. For example, this technology is used in pumped storage power plants (PSPPs) [1]. The pumped storage power plant operation cycle consists of the accumulation of water in the tank with the help of pumps and the subsequent discharge to the hydro turbine.

For this purpose, it is necessary to use ES with high efficiency, but since it is often unprofitable to build and maintain such power plants, it is necessary to consider options with low cost. In this regard, the recently studied gravitational energy storage devices are a promising AES technology.

2 The principle of operation of gravitational energy storage

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The minimum viable version of a system that uses a gravitational energy storage during operation can be a system that includes an elevating platform with a motor generator and a battery. The rise of a certain mass located on the platform from one height to another, higher one, will correspond to the process of energy accumulation, and its descent back to the initial level will correspond to the discharge of energy [2].

The study [3] describes in detail the structure and principle of operation of a power plant based on a gravitational energy storage (GES).

The main component of the GES is a load of mass m directed in the vertical direction (schematically GES is presented in Figure 1). It is driven by a system of cables connected through a system of gearboxes to the motor/generator. The motor-generator is connected to the electrical network through a frequency converter (FC). A block of supercapacitors is connected to the intermediate link of the inverter, which is needed to ensure control of the power level in the network and to ensure the possibility of shutting down the process without delays and power surges.

The load m is subjected to two main forces, firstly the gravitational attraction force Fv, and secondly the traction force Ft that is applied by the cable system and the motor/generator. In the process of accumulation, the electric machine works as a motor; during energy recovery, the machine works as a generator.

3 Formulation of the problem

Scientists at Oxford University analyzed the possibility of placing power plants with GES in abandoned coal mines [4]. An assessment was also made of the potential energy capacity for a large former coal mining region. An analysis of 3,234 mines revealed that the total energy capacity that can be harnessed with the GES technology is 1.07 GWh. Moreover, 340 mines have a maximum energy storage capacity in the range of 1-6.7 MWh. These mines account for 0.804 GWh of available energy for development (74.7% of the total).

In the Russian Federation, the Energozapas company from the Novosibirsk Akademgorodok is currently developing an industrial prototype of a solid-state storage power plant (SSPP). According to the company, the technology will allow the creation of industrial storage devices with a capacity of 300 MWh.

Generation systems based on gravitational energy storage have similar features with wind power plants (WPPs). As well as wind turbines, systems with GES have an intermittent operation mode. In addition, the speed of the rotor depends on the size of the system, kinematic mechanisms, the mass of the load and the height of the platform. Based on this, it can be argued that electric machines as part of systems with GES are low-speed (up to 300 rpm) and medium-speed (300-1500 rpm).

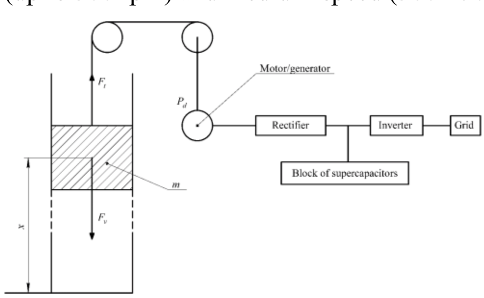

Fig. 1. Structural diagram of a power plant based on a gravitational energy storage device.

Electric generators with electromagnetic excitation have a number of disadvantages, the main of which are: high weight and size; low efficiency and reliability due to the use of brush assemblies. Therefore, in this paper, it is proposed to use a generator with magnetoelectric excitation. PM synchronous generators can be divided into internal and external rotor configurations. The configuration with an external rotor (Figure 2) shows greater efficiency, so it was decided to use this type of generator, the studies presented in [5, 6] confirm the decision.

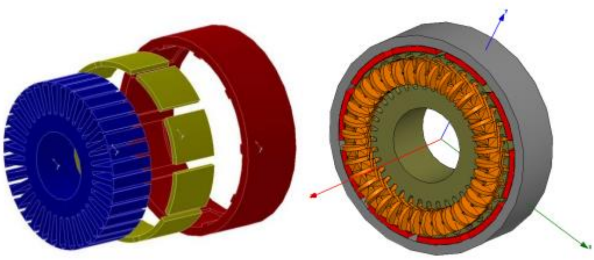

Fig. 2. Permanent magnet synchronous generator with external rotor.

Before setting the task of designing a generator for GES, it was necessary to review the existing technical solutions.

Table 1 presents the results of a search for domestic and foreign manufacturers of low-speed generators with a rated power of 2000 kW.

As can be seen from the data in tables 1, in Russia and abroad, low-speed generators with a rated power of 2000 kW are produced mainly with a rotation speed of 1500 rpm. At the same time, the specific power of the products of the listed manufacturers is in the range from 0.08 to 0.45 kW/kg.

Table 1. Domestic and foreign manufacturers of low-speed generators.

Manufacturer	Country	Model	Rated power, kW	Voltage, V	Rotation frequency, rpm	Weight, kg
1. Synchronous generators						
TSS	Russia	TSS-SA-2000	2000	400	1500	-
2. High voltage stations						
Gazvolt	Russia	Gazvolt 2000T24	2000	6300	1000	23000
3.Synchronous generators						
Leroy Somer	France	LSA 53.2 M7	2120	400	1500	5250
Stamford technology	China	734J	2200	400	1500	4500
4.High voltage stations						
Jenbacher	Austria	J 612 J09	2004	6300	1500	25500

As a result of the review, the task was set to develop a generator with a capacity of at least 2000 kW, with a high specific power, while the implementation of the generator had to take place at low speeds of 12, 20, 100, which can be implemented without the use of a step-up gearbox, also 500 and 1500 rpm, in which it is necessary to use a gearbox. The need to reduce the generator speed is explained by minimizing the cost and dimensions of the system by eliminating the gearbox or using cheaper and more compact solutions with a lower gear ratio. The widespread introduction of generation systems based on RES is hampered by the low efficiency of modern electric machines (EMs). One of the main indicators of the efficiency of EMs is their efficiency and specific power [2]. Therefore, the task was set to evaluate the efficiency of low-speed synchronous generators with permanent magnets as part of a system with GES based on these two indicators.

The design of low-speed PMSGs was carried out using the Ansys Electronics software package.

4 Research and development of high efficiency gravity energy storage generator

According to the known formulas, the main design dimensions of low-speed PMSGs were determined, which were then used for design and analysis by the finite element method in the module Maxwell 2D. Table 2 shows the data of low-speed permanent magnet generators, which are designed for different speeds.

Table 2. Parameters of low-speed generators with permanent magnets.

Options	Rotation frequency, rpm				
	12	20	100	500	1500
Rated power, kW	2156.3	2168.2	2127.6	2169.9	2164.2
Phase voltage, average, V	2012.8	1896.1	1842.8	1822.5	1869.8
Phase current, average, A	402.18	436.96	440.94	439.11	439.75
Current density, A/mm^2	4.67	4.3	4.8	4.32	4.79
Linear current load, A/m	69251.28	39405.83	24684.39	54721.54	22437.56
Rotor outer diameter, mm	3998	3998	2178	1066	879
Mass of the active part, kg	16853.5	14564.1	5493.28	1708.46	1067.27
Specific power, kW/kg	0.13	0.15	0.39	1.27	2.03
Efficiency, %	92.59	95.42	97.71	97.29	98.69

For the stator core, electrical steel 49K2FA was chosen, and for the rotor, electrical steel 2421 with a saturation induction of 2.3 and 1.7 T, respectively. The stator winding was made of copper wire PNET- imide.

The dependence of the main performance indicators of low-speed PMSGs (efficiency and specific power) on the rotational speed is shown in Figure 3.

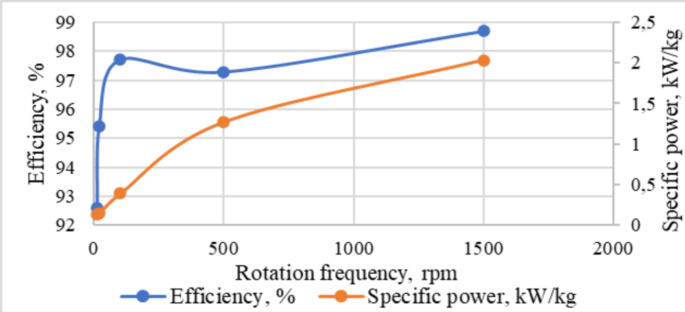

Fig. 3. Dependence of efficiency and specific power on the rotational speed.

This figure shows that the efficiency and power density increase with increasing speed. The best performance has PMSG with a speed of 1500 rpm (medium speed). In comparison with the 12 rpm generator, the increase in efficiency was 6.1%, and the specific power increased by 1.9 kW/kg, which significantly exceeded the achieved indicators of technical solutions of domestic and foreign manufacturers.

If you use a medium-speed generator, then it will require a massive gearbox. This is due to the fact that with an increase in the gear ratio of the gearbox, its mass also increases. Therefore, from an economic point of view, it will be more profitable to use a step-up gearbox and a low-speed generator with a speed of 100 rpm. Thus, the system will receive a gain in the total mass and it will be possible to use the PMSG with a high efficiency. The cost of the system will be reduced due to the lower material consumption compared to the system, which will use a gearless generator at 12 rpm.

Table 3 shows the parameters of the developed low-speed PMSG with a rotation speed of 100 rpm.

Table 3. Parameters of low-speed PMSG.

Parameters	Value	Parameters	Value
Rated power, kW	2127.6	Winding type	Distributed
Rotation frequency, rpm	100	Number of layers/parallel branches	1/1
Number of poles	120	Phase active resistance at 20℃, Ohm	0.0484455
Active length, mm	2000	Brand of magnets	NdFe35 /
Outer diameter, mm	2178	Coverage of permanent magnets	0.95
Phase voltage, average, V	1842.8	Mass of permanent magnets, kg	1409.93
Phase current, average, A	440.94	Winding weight, kg	611.519
Efficiency, %	97.71	Mass of the stator core, kg	1695.26
Power factor	0.87	Rotor core weight, kg	1776.56
Linear load, A/m	24684.39	Active mass, kg	5493.28
Number of stator slots	360	Specific power, kW/kg	0.39

To verify the obtained values, the simulation of electromagnetic processes was carried out using the finite simulation method in the Ansys software package. The rated power, excluding the transient process, turned out to be 2127.6 kW. Since the analytical calculation showed that the mass of the active part of the designed machine is 5493.28 kg, the specific power of the low-speed PMSG will be 0.39 kW/kg.

Figure 4 shows the dependence of the phase voltage and current on time. The average value of the phase voltage of the machine is 1842.8 V and, the average value of the phase current was 440.94 A.

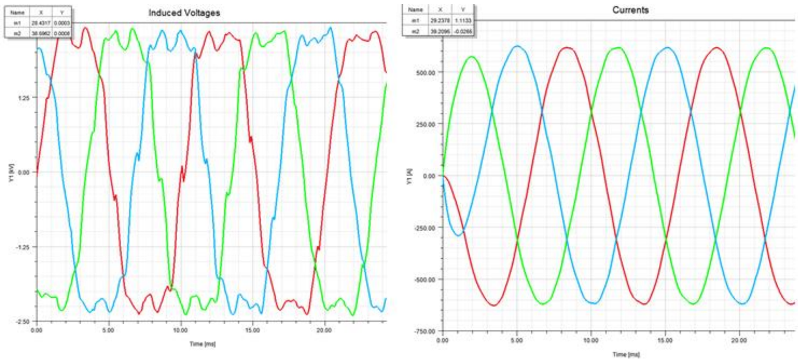

Fig. 4. Dependence of the phase voltage and phase currents on time.

The influence of the harmonic components of the voltage is clearly pronounced. Therefore, it will be necessary to use a frequency converter to make the voltage curve sinusoidal.

The efficiency of the generation system is significantly affected by the cooling system. Therefore, it is necessary to carry out a thermal calculation, first of all, to assess the temperature of the stator winding, since it is one of the most vulnerable parts in case of overheating of the active part of the PMSG. It was preliminary decided to use air cooling, the characteristics of the cooling system correspond to the parameters of the general industrial fan VIR200.

As a result of the analytical calculation, the winding temperature was obtained equal to 129.4 ºC

As a test, it was decided to calculate the thermal distribution in the active part of the low-speed generator using the Motor-CAD software package. The results of the calculation are shown in Figure 9.

In Figure 5, on the left is the temperature distribution in the stator winding, on the right – in permanent magnets. The value of the maximum temperature of the stator winding was 135.1ºC, therefore, it is acceptable for the selected brand of wire. The analytical calculation error was 4.4%.

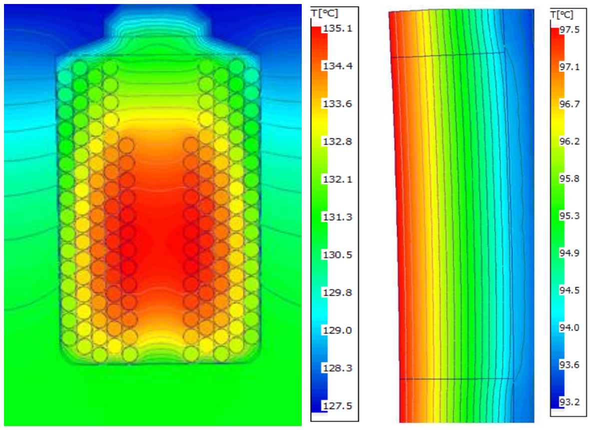

Fig. 5. Thermal distribution in the active part of a low-speed generator.

5 Conclusion

To summarize the above, it can be argued that, simultaneously with the development of generation systems using renewable energy sources, there is a need for the development of electricity storage devices, in particular, those based on the action of gravitational forces. GES are distinguished by a simple principle of operation and are mainly used as part of power plants to equalize the schedule of daily energy consumption. When designing power plants based on GES, it is necessary to take into account the uneven load and select electrical equipment according to the tasks the system will be directed to solve.

Based on the results of the study, it was proposed to use a low-speed generator with permanent magnets and an external rotor in systems with a gravitational energy storage device. To increase the economic efficiency of this power system, the use of a step-up gearbox is required. In the process of designing a low-speed PMSG, it was possible to achieve an efficiency of 97.71% and a specific power of 0.39 kW/kg (for the active part).

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