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Experimental Study of a Gravity-Based Energy Storage System with a Dual-Mode DC Motor Drive

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ABSTRACT With the rapid development of renewable energy sources and the need to ensure reliable energy supply, research into effective energy storage systems is becoming particularly relevant. This article discusses one promising method: a gravitational energy storage system based on the principle of lifting and lowering a load, followed by the conversion of potential energy into electrical energy. A design diagram of an experimental gravitational system has been developed and presented, including a lifting mechanism, load, guide elements, and a DC motor operating in two modes: motor mode (lifting the load) and generator mode (lowering the load with electricity generation). As part of the experiment, the relationships between the mass of the load, its speed of movement, and the overall efficiency of the system were determined. The study paid particular attention to the influence of the load mass on the efficiency of the installation. The results obtained can be used in the development of industrial prototypes of gravitational energy storage systems, as well as in local and distributed power supply systems, especially in combination with solar and wind power plants.

I. INTRODUCTION

Gravity energy storage systems are a type of mechanical energy storage system. Their main principle of operation is the conversion of electrical energy into potential energy when masses are lifted to a certain height, and the reverse conversion — potential energy into electrical energy — when the load is lowered [1]. These systems are particularly relevant in the field of renewable energy sources, as they compensate for uneven generation by accumulating excess energy and returning it to the grid during peak consumption hours [2].

A number of studies have examined various architectures of gravity storage systems, ranging from classic hydraulic tower structures to compact mechanical systems with counterweights. Study [3] analysed the efficiency of gravity storage systems under variable load conditions and found that they can be successfully used to compensate for unstable energy production by solar and wind power plants. The authors [4] proposed modular vertical structures with automatic control, capable of operating both at the level of residential complexes and on an industrial scale.

Particular attention is paid in the literature to the choice of drive equipment. In works [5, 6], a direct current motor (DCM) is considered as a universal element capable of functioning both in drive mode and in generator mode. This makes DCM particularly attractive for use in compact gravity systems. However, researchers note that the efficiency of such systems significantly depends on the motor parameters, the inertial characteristics of the load, and the accuracy of the operating mode control [7-9].

In [10], data on the change in the efficiency of a gravitational installation depending on the mass of the transported load is presented. It has been established that as the mass increases, the level of regenerated energy increases, but mechanical losses and the load on the lifting system also increase [11]. The authors emphasise the need to optimise the mass of the load and its speed of movement to achieve maximum efficiency.

At the same time, the integration of gravity-based energy storage system into existing power grids remains a pressing issue. Publication [12] discusses aspects of controlling and forecasting the operation of gravity storage systems in Smart Grid conditions, which opens up prospects for their automation and large-scale application.

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Thus, an analysis of existing scientific publications confirms the relevance of the research topic. Despite the positive results obtained in a number of studies [13-17], there is still a need for practical experiments aimed at refining the characteristics of the installation in real conditions, which served as the basis for this article.

II. METHODS AND MATERIALS

Figure 1 shows a diagram of the gravitational storage system.

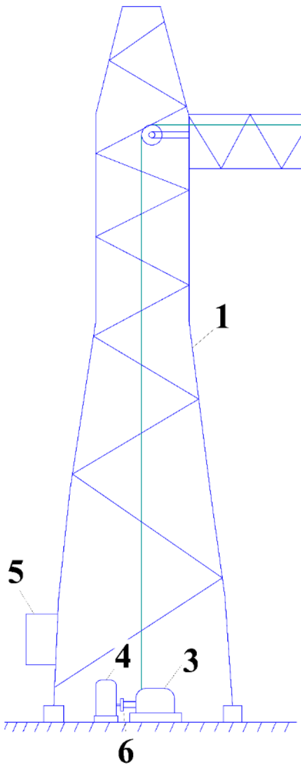

Fig. 1. Schematic diagram of a gravity installation

Fig. 1 shows the following elements of the gravitational system:
1 – L-shaped support, where the maximum lifting height of the load is 18 metres;
2 – load, consisting of concrete blocks, the total mass of which will vary during the experiment from 100 to 310 kg;
3 – drive;
A P-32 DC motor with the following parameters (Table 1) will be used as the drive.

Table 1. Technical parameters of the P-32 drive

Active power, kW	Nominal voltage, V	Nom. current, A	Nominal rotation speed, rpm	Efficiency,	Moment of inertia, kg·m²	Excitation
2,2	110	24,5	1500	67,5	0,029	Mixed

4 – gearbox with a transmission ratio of 25:1;
5 – control panel for switching between generator and motor modes of the drive, equipped with measuring instruments for measuring parameters;
6 – coupling equipped with a brake mechanism necessary for securing the load at height;
7 – roller mechanism;
8 – cable.

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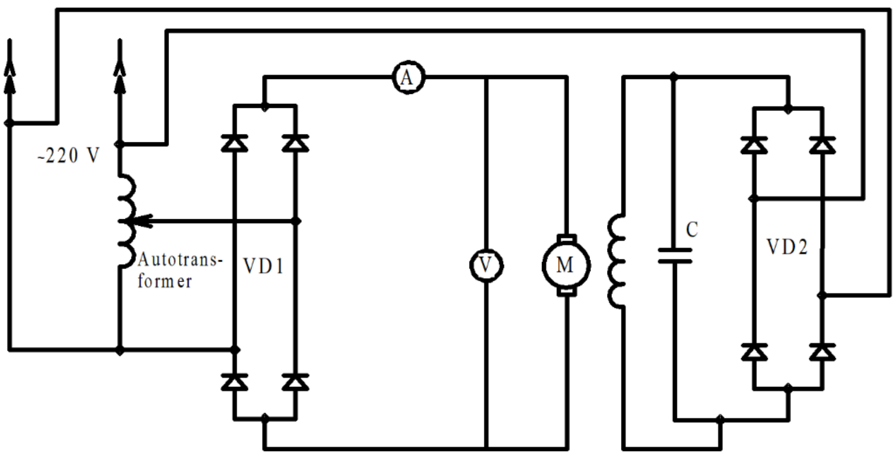
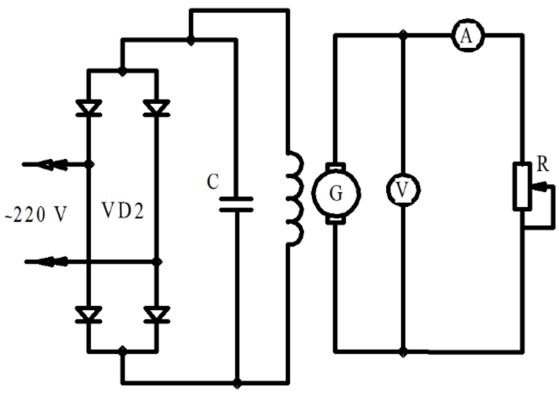
Let us take a closer look at the electrical diagrams for the P-32 drive operating in motor and generator modes. Figure 2, a shows the drive control diagram in motor mode, i.e. when lifting a load to a height. Figure 2, b shows the control diagram in generator mode.



a)



b)

Fig. 2. Schematic diagrams of the connection of the drive P-32 of the gravity installation

In the diagram (Fig. 2, a), the drive is powered from a single-phase 220 V network. The autotransformer is designed to regulate the voltage supplied to the armature winding. During the experiment, the voltages will be set to 55 and 110 V. Rectifiers VD1 (I_{nom} = 100 A) and VD2 (I_{nom} = 75 A) are designed to convert the AC mains voltage to DC. The armature winding is connected to VD1, and the excitation winding to VD2. The capacitance C in the excitation circuit is designed to suppress voltage ripples and reduce voltage surges during sudden changes in current. In the generation mode, an active resistance R = 8.5 Ohm is connected to the armature circuit of the drive, and the rectified mains voltage is applied to the excitation winding.

The choice of a separately excited DC motor is determined by the following factors: constant angular velocity, good overload capacity, flexibility in controlling motor characteristics. At the same time, the following points must be taken into account: high armature current during starts, the need to supply the excitation winding from a DC source. To conduct the experimental part of the study aimed at obtaining data on the physical implementation of the gravitational installation, the design shown in Fig. 1 was prepared. The experiment was planned to be conducted in calm weather to exclude the influence of wind on the lifted/lowered load (sail effect). The following equipment was prepared: P-32 electric motor; measuring instruments (ammeter, voltmeter, electric stopwatch, etc.); power supply; rectifiers; loads of various masses; cable.

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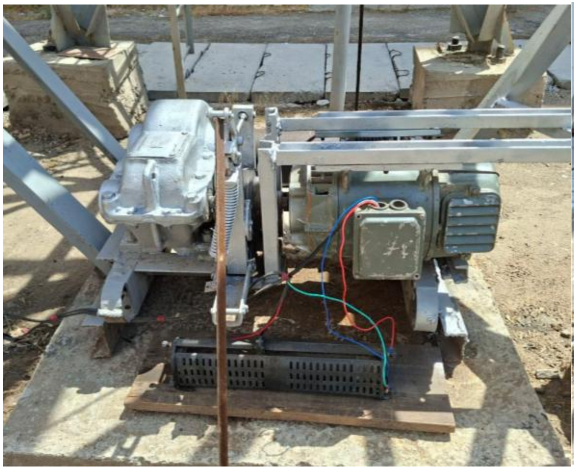

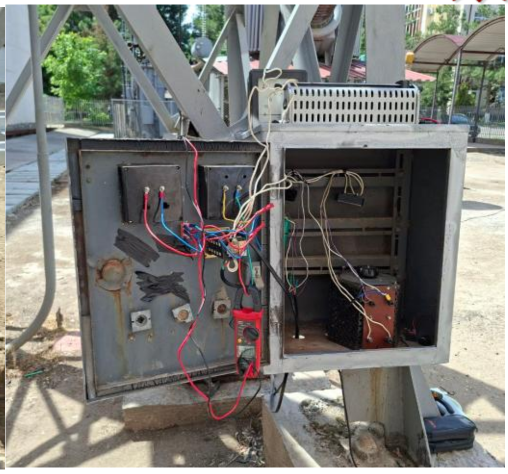

a) b)

c)

Fig. 3. Experimental setup of a gravitational energy storage system

Figure 3, a shows a photograph of the drive connection to the gearbox, as well as the resistance used as a load. Figure 3, b shows a photograph of the control cabinet designed for switching between engine and generator modes. And Figure 3, c shows a general view of the experimental gravitational energy storage system.

As part of the preparations for the experiment, the circuit shown in Fig. 2 was assembled and tables were prepared for recording the results. During the lifting and lowering of the loads, the voltage and current of the armature were measured and the time was recorded. To prevent accidental errors, each cycle (lifting and lowering) was performed three times to determine the average values of the current (I_{avg}), voltage (U_{avg}) and time (t_{avg}) parameters.

In addition, to ensure the safety of the work, the reliability of the load fastening was checked. The possibility of people being under the load during lifting/lowering was also eliminated by installing barriers. When in the vicinity of the installation, helmets and safety equipment were used.

In order to ensure the most efficient mode in terms of maximum efficiency when lifting the load, voltages of 55 V and 110 V were applied to the anchor. The results are summarised in Table 2.

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IJARSET IMPACT FACTOR 7.150

Table 2. Experimental results

№	m, kg	Driving mode					Generator mode				
		U_{avg}, V	I_{avg}, A	t_{avg}, sek.	E_1, J	η_1, %	U_{avg}, V	I_{avg}, A	t_{avg}, sek.	E_2, J	η_2, %
1	100	55	8,73	54,33	26098,11	67,66	34,33	4,6	68,33	10799,93	61,16
		110	9,4	31	32054	55,08					
2	125	55	9,34	55,33	28434,88	77,62	39,33	5,22	64,66	13294,32	60,23
		110	11	29,33	35493,33	62,18					
3	150	55	11,86	57,33	37419,56	70,78	50,33	7,06	48,66	17310,19	65,35
		110	12,86	28,66	40572,89	65,28					
4	175	55	12,53	53,33	36764,44	84,05	60	8,03	40,66	19601,33	63,43
		110	14,76	27,33	44398,44	69,6					
5	200	55	14,53	54	43164	81,81	64	8,6	39,33	21649,07	61,30102
		110	15,36	31,33	52963,78	66,68					
6	225	55	16,56	57,66	52543,94	75,61	75,66	10,46	31,33	24815,3	62,46
		110	17,83	28,33	55580,56	71,48					
7	250	55	17,53	59,66	57538,56	76,72	80	11,03	30,33	26774,22	60,65
		110	18,76	31	63994,33	68,98					
8	275	55	20,03	57,33	63171,78	76,87	93	13,16	25,33	31020,67	63,88
		110	21,46	28,66	67691,56	71,73					
9	300	55	22	60,66	73406,67	72,16	102	14,66	23	34408	64,95
		110	23,43	30	77330	68,5					

III. RESULTS AND DISCUSSING

The amounts of energy expended during lifting (E1) and generated (E2) during the descent of the load were determined, followed by the determination of the efficiency of the installation during lifting ($\eta 1$) and descent ($\eta 2$).

Figure 4 shows the dependence of efficiency on the mass (m) of the load used in the lifting and lowering modes.

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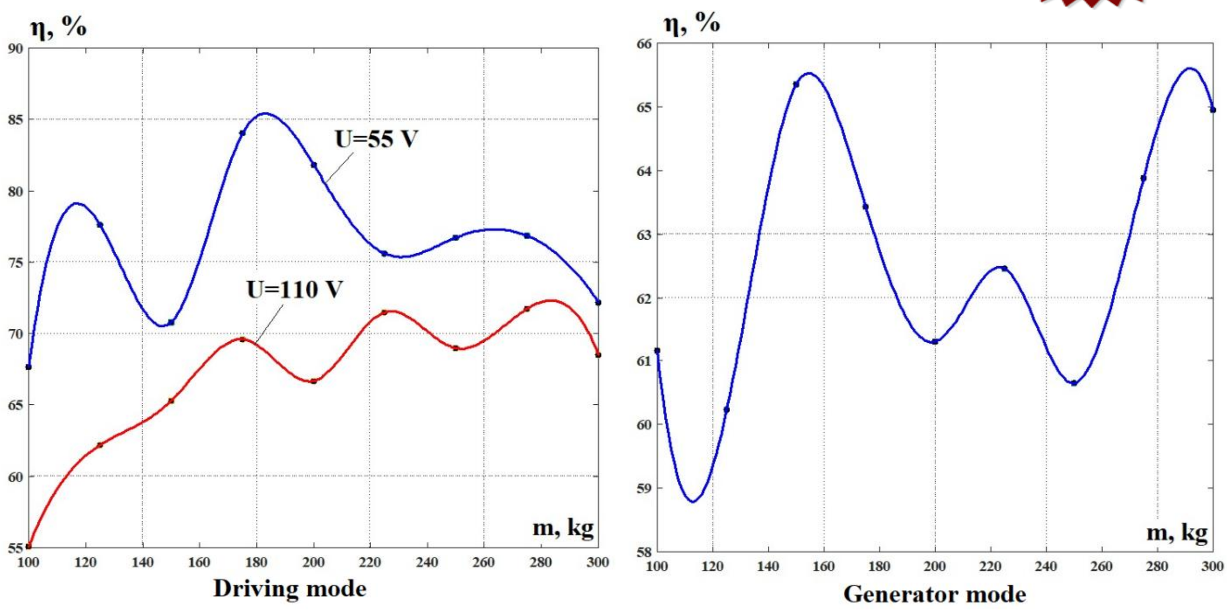

Fig. 4. Curve showing changes in the efficiency of the gravity installation

In load lifting mode, supplying 55 V DC voltage to the motor armature winding resulted in higher efficiency. This can be explained by the fact that a decrease in voltage and a constant mechanical load reduce the current, which leads to a decrease in power losses in the motor armature.

Conclusion. The results showed that as the load mass increases, the amount of energy generated also increases, but the efficiency of the system does not increase proportionally — this is influenced by a combination of factors, including mechanical losses, inertial loads, and electrical losses in the energy conversion system.

IV. CONSOLATION

The results showed that as the load mass increases, the amount of energy generated also increases, but the efficiency of the system does not increase proportionally — this is influenced by a combination of factors, including mechanical losses, inertial loads, and electrical losses in the energy conversion system.

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