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An automatic frequency control system for off-grid power systems with energy storages

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SUMMARY

Background. Off-grid power systems located in remote areas are characterized by extremely high cost of electricity due to the large fuel component. Solutions aimed at reducing diesel fuel costs in industrial off-grid power systems are limited due to abruptly variable load. Gas piston generators in the presence of abrupt load changes have difficulty maintaining the frequency and can be turned off by protections. Autonomous Hybrid Power Plants (AHPP), which include fossil fuel generators, renewables and Electrical Energy Storage Systems (EESS), aggravate the problem of frequency control because of the stochastic nature of renewables. To solve the problem, it is proposed to use the EESS, which smooths out load changes and stabilizes the frequency. Thus, it is necessary to develop an automatic control system that takes into account the technical characteristics and features of EESS.
Materials and methods. To obtain data on the operating parameters of a power plant, a monitoring of regime modes was carried out. Mathematical modeling methods in the MATLAB/Simulink environment are used to develop, test and study the effectiveness of control algorithms for EESS and AHPP as parts of an off-grid power system. The calculations are carried out using a mathematical model, the accuracy of which was confirmed by comparing the results of computational and natural experiments. In addition, the methods of the signal processing, the instantaneous power theory, the simulation modeling, the automatic control, the optimization, the fuzzy logic are used. To solve the optimization problem, the simplex method is used.
Results. The requirements for the frequency control system were formulated. The maximum frequency deviation in an off-grid power system should be limited to ±0.2 Hz to ensure its effectiveness for sensitive consumers and generators. A method of frequency control was proposed, combining control by disturbance and frequency deviation, which allows eliminating shock changes in frequency and reducing its deviations to the required level. An algorithm was developed for distributing the shares of involvement in regulating of different storages as parts of a hybrid energy storage system. An algorithm was developed to maintain the charge level of the energy storage by deliberately strengthening or weakening engagement in regulation. The concept of an automatic frequency control system in a power system with an AHPP was proposed with the creation of a power reserve of the Solar Power Plant (SPP) and the distribution of control actions between the EESS and SPP. A procedure was proposed for selecting the parameters of frequency controllers based on optimization. The effectiveness of control algorithms was confirmed by calculations based on a mathematical model of an off-grid power system with standard load diagrams and with an abruptly variable energy consumption of an industrial facility.
Conclusions. The developed automatic control system makes it possible to reduce the maximum frequency deviation in off-grid power systems with abruptly variable load to a value of 0.2 Hz and less. Even without optimizing the diesel generator speed controller, the required quality of electricity is ensured by involving the EESS and SPP (in some periods of time) in the regulation. Due to the algorithm for maintaining the charge level and the small value of the energy intensity involved in regulation, the involvement of EESS in frequency control as an additional function does not require significant capital investments, but makes it possible to satisfy the individual requirements of electric consumers sensitive to frequency deviations and expand the field of application of AHPP and gas piston generators in off-grid power systems with abruptly variable load.

KEYWORDS

Off-grid power system - Electrical energy storage system - Autonomous hybrid power plant - Solar power plant - Gas piston generator - Diesel generator - Automatic control system - Frequency control - Abruptly variable load - Power quality

1. INTRODUCTION

There are thousands off-grid power systems providing electricity to populated areas and industrial enterprises of the fuel, energy and mineral resource complex located in the northern regions of Russia. They are characterized by expensive logistics in the supply of materials, equipment and especially fuel. The cost of electricity values reaches 5–55 times higher than average cost in Russia [1].

In off-grid power systems of industrial enterprises, the rated power of the power plant (usually from 0.1 to 25 MW) is comparable to the power of the largest electrical receiver. Changes of its operating mode lead to an abrupt change in regime parameters. With frequent repetition of operations, such a load is usually classified as abruptly variable. It leads to shock changes in frequency (large and rapid) dangerous for generating units and electrical drives and reduces the service life of equipment.

The basis of off-grid energy supply is diesel generators. Their main disadvantage is the high cost of fuel, and with an abrupt change in load, fuel consumption increases even more. Off-grid power systems of oil and gas production enterprises are also equipped with gas piston generators operating on associated or natural gas produced on site. However, due to the inertia of the fuel path, the gas piston generators are less successful in maintaining the frequency under abruptly variable load than the diesel generators. In addition, if the frequency deviates by more than 1.0–1.5 Hz within 0.2 s, the gas piston generators are switched off by their technological protections [2, 3]. To avoid this and to maintain the frequency, it is common to overestimate the installed capacity of a power plant that leads to increased capital costs. An alternative is the installation of Electrical Energy Storage Systems (EESS) at power plants to smooth out load changes, reduce the amplitude of frequency deviations and the rate of its change [4].

At the present time, a popular solution is also an Autonomous Hybrid Power Plant (AHPP), which includes fossil fuel generators, a renewable energy source and an EESS. The stochastic nature of renewables complicates the frequency control under conditions of abruptly variable load and limits the field of application of AHPP.

In all the described cases, due to the versatility and response time of EESS [5], it is advisable to use them in frequency control. Therefore, it is necessary to develop an automatic frequency control system adequate to the technical characteristics and features of EESS. There are many articles on the use of EESS for frequency control [6–8], but the issues of taking into account the characteristics of the load of off-grid power systems, storage's state of charge, and coordinating involvement in the regulation of different energy sources remain topical.

The proposed research offers the control methods and algorithms that make it possible to use an EESS to stabilize the frequency in an off-grid power system with an abruptly variable load, considering the characteristics of the EESS.

2. ANALYSIS OF LOAD DIAGRAM AND FREQUENCY DEVIATION IN OIL FIELD OFF-GRID POWER SYSTEM

To determine the requirements for the frequency control system, an analysis of a typical load diagram of an off-grid power system of an oil field was carried out. To obtain data, monitoring was performed at a diesel generator power station with a capacity of 3000 kW providing electricity to the BU 4500/270 EK-BM drilling rig, as well as other systems of the oil field. Processing of monitoring results, based on the theory of instantaneous power by H. Akagi [9], provided complete picture of processes in the power system during 96 hours of recording technological operations. Figure 1 shows graphs of active power and frequency. Table 1 presents generalized indicators of frequency.

The load power varies from 50 to 2300 kW. There are more than 100 load changes exceeding 30% of the power plant rated power. In many cases, these changes exceed 70% of the load at the previous moment. This operating mode is acceptable for diesel generators, but unacceptable for gas piston generators [2–4]. Therefore, a power plant equipped with the latter and operating according to an identical load schedule must have an increased installed capacity.

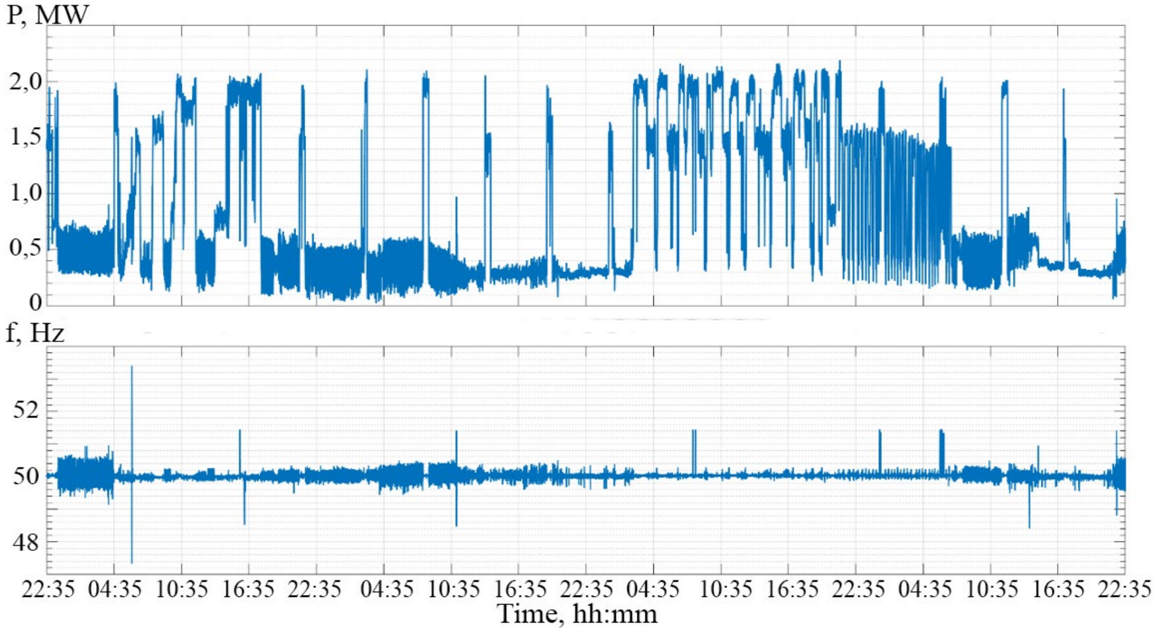

Figure 1 – Power plant load diagram and frequency graph

Table 1 – Frequency monitoring results

Parameter name	Value
Average frequency value, Hz	50.02
Minimum frequency value, Hz	47.32
Maximum frequency value, Hz	53.41
Standard deviation of frequency, Hz	0.044
Standard deviation of rate of change of frequency, Hz/s	0.158

In general, the diesel generators successfully manage the goal of maintaining the frequency. The largest frequency deviation exceeds 3.4 Hz but does not exceed the maximum permissible value according to the standard GOST 32144 (international standard maintained by the Euro-Asian Council for Standardization, Metrology and Certification): ±5 Hz [10]. Many times, the frequency deviation exceeds 1 Hz, but the total time of that fits into a time interval of less than 5%, which is also relevant to GOST. At the same time, short-term but significant and rapid frequency deviations increase wear, decrease the reliability and performance of equipment. Therefore, if there are high-tech power receivers that are sensitive to the power quality, owners often set stricter frequency requirements than GOST.

The frequency control system must ensure the efficient operation of electrical receivers and acceptable operating modes for fossil fuel generators, as well as renewables and EESS. To ensure the possibility of using a control system in the presence of electrical receivers and generators that are sensitive to frequency changes, it was decided to limit the maximum frequency deviation as in the United Power System of Russia: ±0.2 Hz [11] (subject to the condition that the EESS is able to participate in active power control). Shock changes in frequency should be minimized to acceptable values determined by the most sensitive equipment.

3. STORAGE SYSTEM CONTROL ALGORITHMS FOR FREQUENCY STABILIZATION IN A POWER SYSTEM WITH FOSSIL FUEL GENERATORS

To develop and test control algorithms, a mathematical model of an off-grid power system including diesel generator, EESS [12], load (with the possibility of setting an arbitrary load diagram) was created in the MATLAB/Simulink environment.

The disturbance control algorithm (**EESS control algorithm No. 1**) is designed to smooth abrupt load changes. The algorithm provides compensation for the power imbalance upon its occurrence, while the frequency has not yet deviated. The block diagram of the algorithm is shown in Figure 2. The dead zone saves the resource of the EESS.

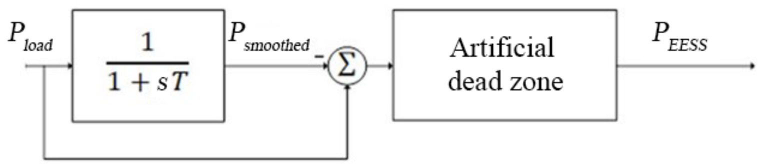

Figure 2 – Block diagram of the EESS control algorithm No. 1

Figure 3 shows the transient process with an abrupt change in the load from 0.2 to 1.0 p.u. and back after 13 seconds in the case when the EESS is not involved in frequency control, which is performed only by means of the diesel generator. Figure 4 shows a process with a similar disturbance when the EESS is involved in control with algorithm No. 1 (the diesel generator is also involved in control).

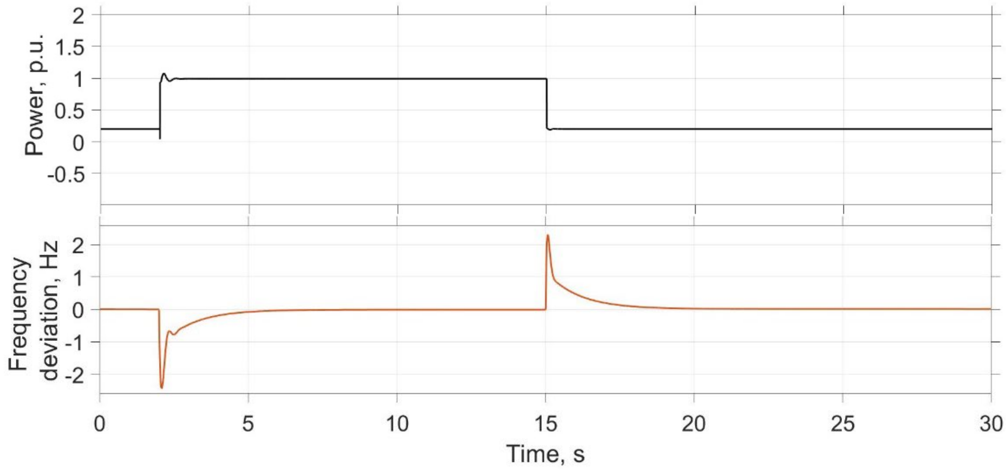

Figure 3 – The transient process without the involvement of the EESS in control

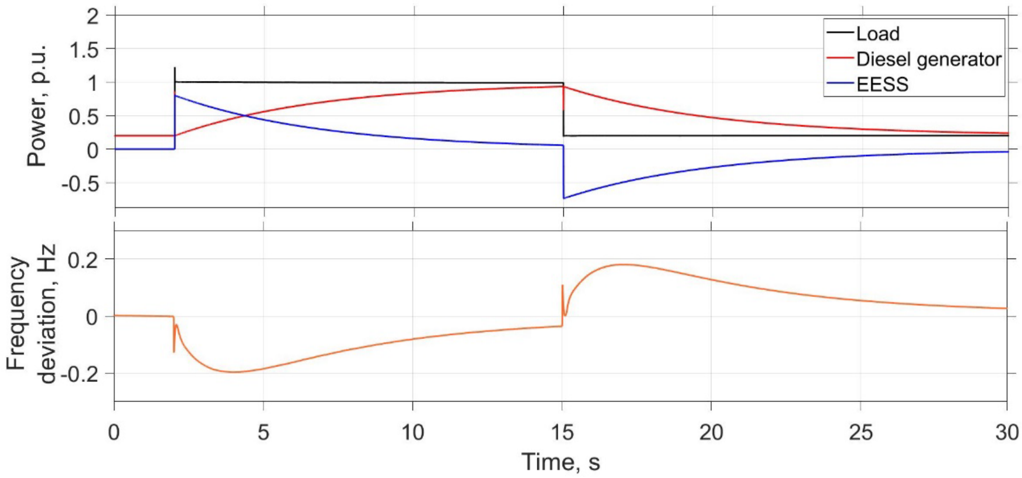

Figure 4 – The transient process with the control by algorithm No. 1

The EESS compensates the load change and exponentially transfers it to the diesel generator with a time constant *T*. Smooth change of frequency is ensured, its deviation is reduced. The short-term frequency surge at the beginning of the transient process is caused by the presence of a response time of the EESS (5 ms).

The deviation control algorithm (**algorithm No. 2**) is built on the PD-principle (Figure 5). The transient process with engagement of the EESS with algorithm No. 2 is shown in Figure 6. The frequency deviation is smaller compared to the simulation with the algorithm No. 1, but there is a shock frequency change immediately after the disturbance.

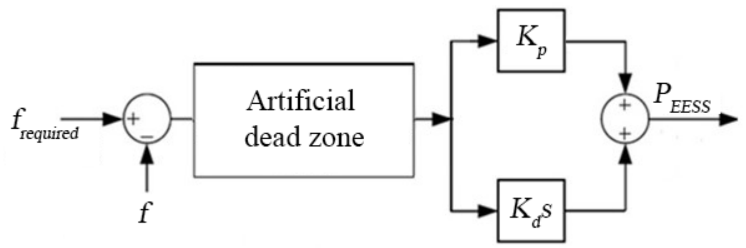

Figure 5 – Block diagram of the EESS control algorithm No. 2

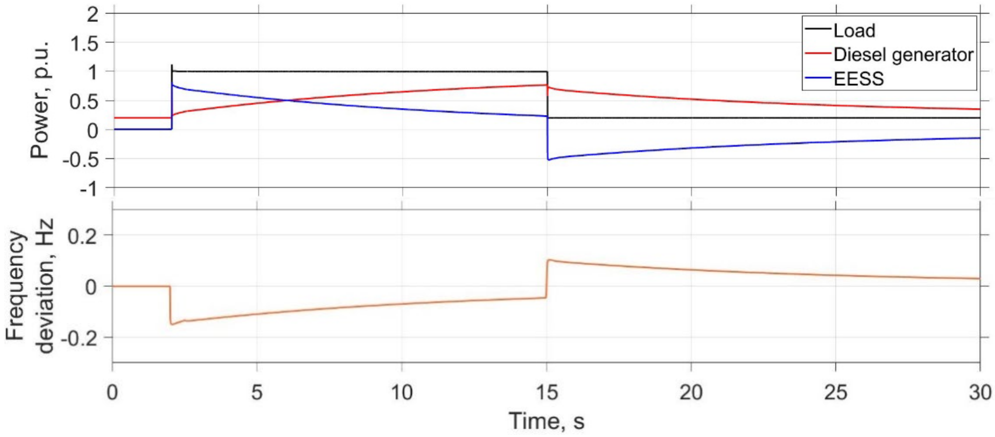

Figure 6 – The transient process with the control by algorithm No. 2

Thus, the **algorithm No. 3** is proposed as better solution. It combines control by disturbance and frequency deviation (Figure 7). The transient process with engagement of the EESS with algorithm No. 3 is shown in Figure 8. This combination of the two control methods reduces frequency deviations and eliminates shock changes more efficiently, which is critically important for sensitive consumer mechanisms and some generators (for example, gas piston generators) [2–4].

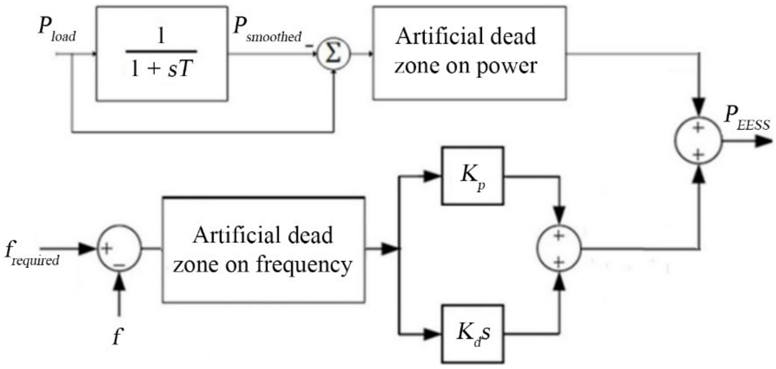

Figure 7 – Block diagram of the EESS control algorithm No. 3

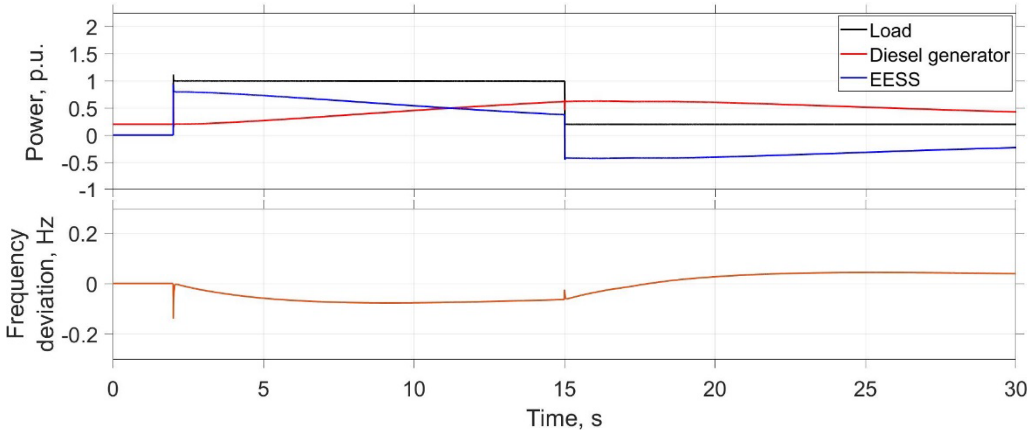

Figure 8 – The transient process with the control by algorithm No. 3

For the distribution of control actions between lithium-ion (Li-ion) and supercapacitor (SC) storages as parts of a hybrid EESS, the **algorithm No. 4** with a dynamic change in gain coefficients was developed on the base of [13]. The power of storages at each moment of time are determined by the gain coefficients of K_{SC} and K_{Li} (Figure 9), which vary over time so that the control mainly involves SC (which has a greater number of charge-discharge cycles) at the first moment after the disturbance. Next, the Li-ion storage (it has higher energy intensity) gradually enters into regulation. This ensures an extension of the storage's service life.

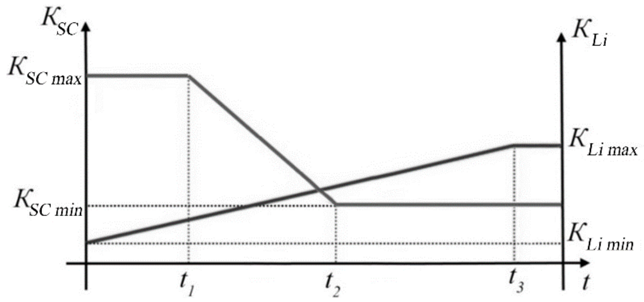

Figure 9 – Time dependence of the gain coefficients of SC and Li-ion storages

To increase its efficiency, the controller proposed in [13] is complemented by a derivative element (Figure 10) with a coefficient $K_{d\,SC}$ that also varies over time. This ensures more intensive use of SC at the beginning of the transient process (Figure 11).

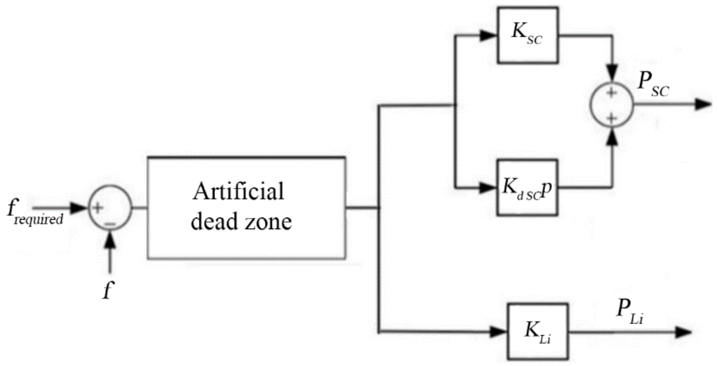

Figure 10 – Block diagram of the EESS control algorithm No. 4

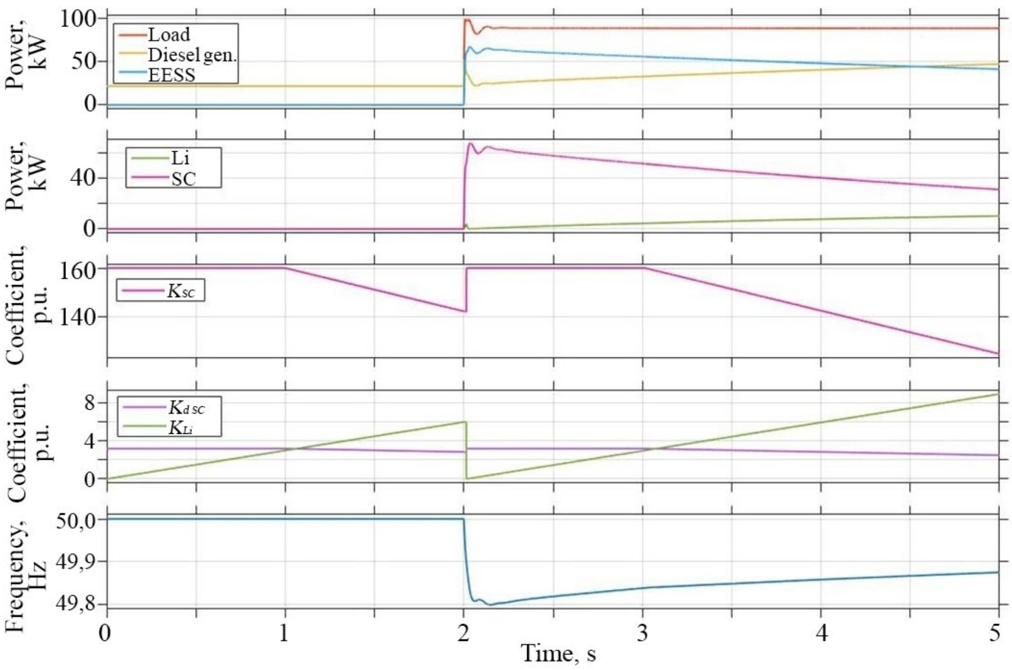

Figure 11 – The transient process after load surge with the hybrid EESS

A feature of the EESS is the limited control resource: a fully discharged or charged EESS is limited in the possibilities of energy exchange. Furthermore, going beyond the recommended state of charge leads to battery degradation and a change of the available power of the EESS [14, 15]. To increase the readiness of the EESS to engage in the control process, the **algorithm for maintaining the charge level** is developed.

When the absolute difference between the current state of charge *SOC* and the state of charge setpoint $SOC_{set.}$ exits beyond the boundary values k_1, k_2, k_3, the signal of the power P_{EESS} required from the EESS decreases (if below the boundary) or increases (if above the boundary) to P'_{EESS} by the correction factors a, b, c (Figure 12).

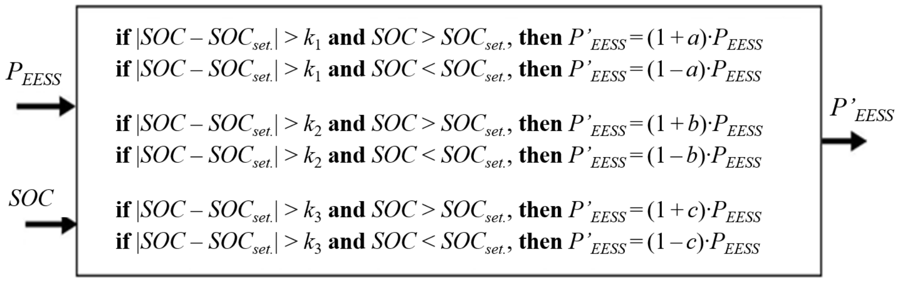

Figure 12 – Algorithm for maintaining the charge level

By means of intentional adjustment of the EESS engagement in frequency control, the charge level is maintained with acceptable reduction of the control quality: the charge level in the example (Figure 13) fluctuates around a certain value. While the algorithm is off, the charge level is constantly decreasing and by the end of the considered period it is 20% lower than with activated algorithm.

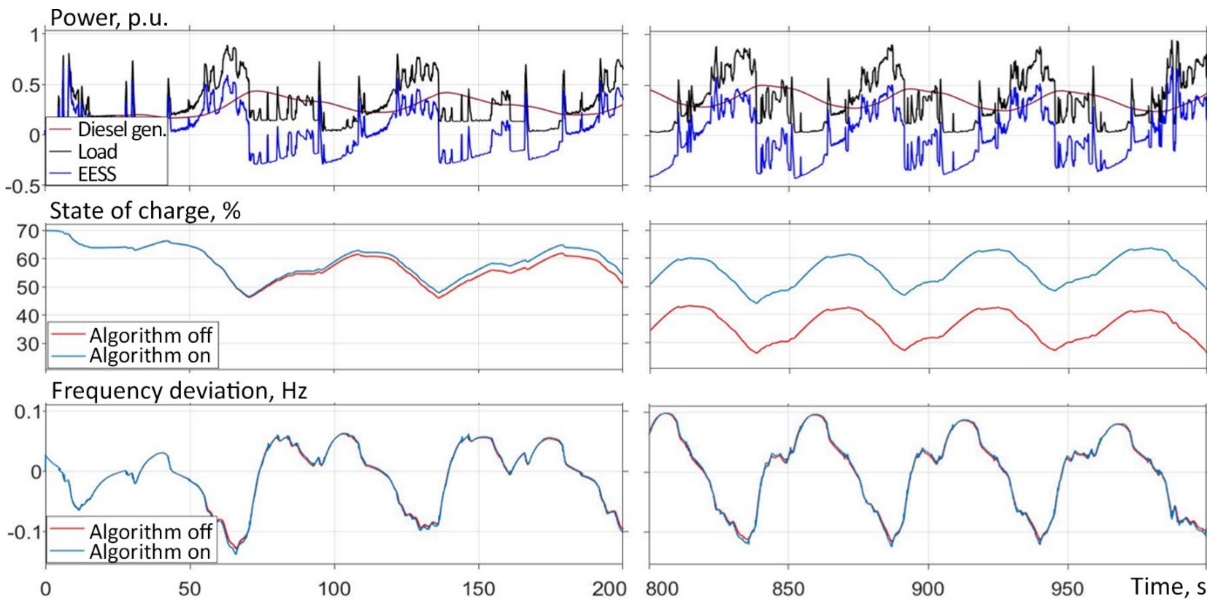

Figure 13 – The transient process in the power system with the algorithm for maintaining the charge level of the EESS and without it

4. CONTROL ALGORITHMS FOR FREQUENCY STABILIZATION IN A POWER SYSTEM WITH AN AUTONOMOUS HYBRID POWER PLANT

The composition of the off-grid power system model in the MATLAB/Simulink is supplemented by a Solar Power Plant (SPP). The architecture of the developed automatic frequency control system is presented in Figure 14. To implement the proposed control system, each energy source in the AHPP should have its own frequency controller. The proposed **method for selecting controller parameters** is based on optimization (minimization) of the objective function. An individual objective function is selected for each energy source. The search for the minimum value of the objective function is carried out using the Response Optimization tool in MATLAB/Simulink. The simplex method is used.

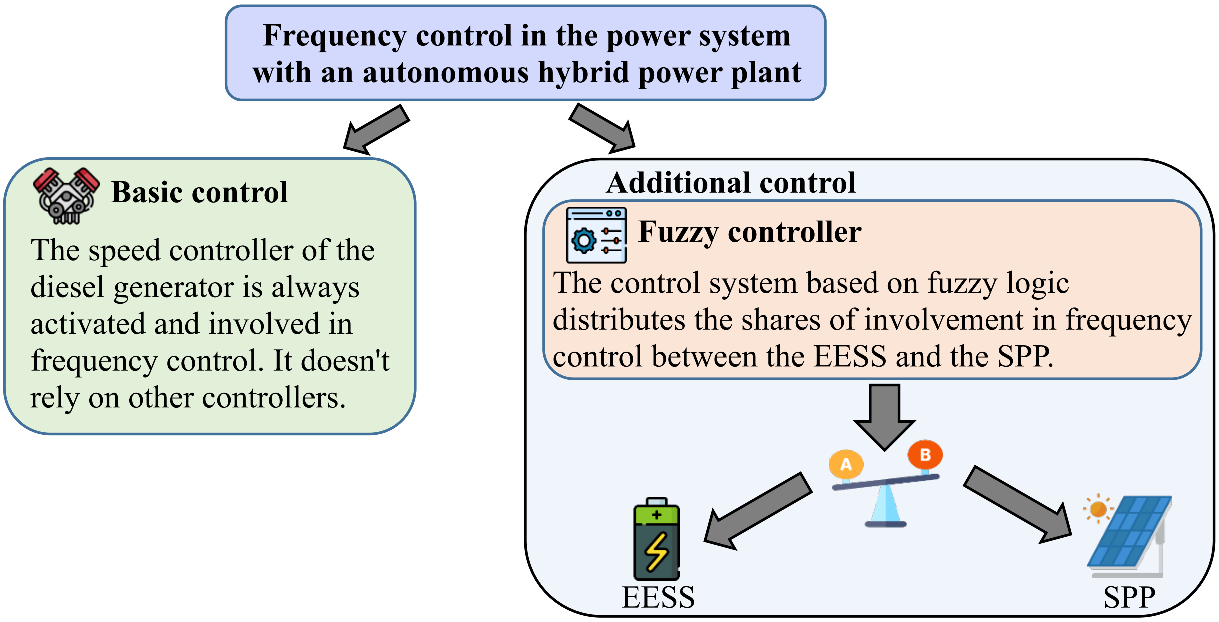

Figure 14 – The concept of the automatic frequency control system

If it is possible to change the parameters of diesel generator speed controller, the integral of time-weighted absolute error [16] is used as the objective function (1). At first after the disturbance, the main role in frequency control belongs to the EESS. It is important that the diesel generator maintains the frequency value over longer time intervals. It is provided by the selected function that reduces the influence of the disturbance at the first moment of time on the value of the objective function.

$$C = \int (|(f_0 - f)|^2 \cdot t)\, dt, \quad C \to min, \tag{1}$$

where f_0 – nominal system frequency; f – current frequency value; t – time.

For EESS, the difference between the required (desired) exchange energy intensity $E_{req.}$ and the energy intensity used in control E_{used} is chosen as the object function (2). Limiting the engagement of EESS by the required exchange energy intensity saves the battery life. Any value of $E_{req.}$ can be set, which will provide the required frequency indicators.

$$C = |E_{req.} - E_{used}|, \quad C \to min \tag{2}$$

For SPP, frequency control is not the main task. SPP engaged in regulation as necessary. The objective function is the difference between the required (desired) frequency deviation $\Delta f_{req.}$ and the maximum frequency deviation recorded in the calculation.

$$C = \left|\Delta f_{req.} - |(f - f_0)|\right|, \quad C \to min \tag{3}$$

To ensure the rational use of the EESS, SPP and fossil fuel generator in the frequency control, the **algorithm for coordinating the joint operation of heterogeneous energy sources** is developed. It involves redistributing the share of energy sources in control depending on their current state. The algorithm is created using fuzzy logic (MATLAB Fuzzy Logic Toolbox). The coefficients of EESS and SPP engagement in control vary in the range from 0 to 1, their sum remains equal to 1. The diesel generator is always involved in control, the coefficients do not apply to it. Based on the membership functions and a set of rules, the dependence of the coefficient on the charge level is formed. When the charge level deviates from the desired value and converges with the limits of the operating range, the proportion of EESS engagement decreases.

The algorithm may provide an adaptive reserve of the power of the SPP in order to be able to use it in frequency control, if necessary. The type of SPP involvement in regulation is also determined by the fuzzy controller. With the type «0», the SPP is not involved in control. With the type «1» it can increase or decrease power to control frequency. At intermediate values, the SPP can only reduce its power.

To **test the effectiveness of the developed control system**, a series of calculations were performed using a model of an off-grid power system with load graphs corresponding to the operating modes of the S4, S5, S7 according to GOST IEC 60034-1 [17], and power consumption diagram of the KPL 18-82 crane mechanisms. This type of load was chosen because lifting mechanisms of cyclic action are characterized by one of the highest degrees of unevenness of the energy consumption schedule among all consumers. Four configurations of energy sources and settings of their controllers were considered:

1. Diesel generator – controller with standard settings;
2. Diesel generator – optimized controller;
3. Diesel generator – controller with standard settings; EESS, SPP – optimized controllers;
4. Diesel generator, EESS, SPP – all controllers are optimized.

Table 2 shows generalized frequency indicators. Figure 15 shows an example of a transient process during operation of the configuration No. 4 with the load schedule of the KPL 18-82. The positive value of the EESS power corresponds to the consumption of energy from the power system.

Table 2 – Generalized frequency indicators

Energy source configuration number	**Parameter name**			
	Standard deviation of frequency, Hz	**Standard deviation of rate of change of frequency, Hz/s**	**Average value of frequency deviation, Hz**	**Maximum value of frequency deviation, Hz**
Electrical drive power consumption mode S4				
1	0.539	2.831	0.168	3.514
2	0.231	2.760	0.067	1.741
3	0.037	1.246	0.028	0.112
4	0.029	1.399	0.022	0.089
Electrical drive power consumption mode S5				
1	0.619	3.034	0.197	4.342
2	0.250	2.721	0.070	2.161
3	0.052	1.120	0.038	0.127
4	0.040	1.293	0.029	0.099
Electrical drive power consumption mode S7				
1	0.423	0.718	0.164	3.248
2	0.140	0.340	0.054	1.038
3	0.016	0.005	0.011	0.050
4	0.015	0.006	0.010	0.045
KPL 18-82 crane mechanisms power consumption diagram				
1	0.757	2.829	0.473	4.533
2	0.316	1.603	0.254	1.151
3	0.055	0.052	0.044	0.137
4	0.035	0.054	0.029	0.086

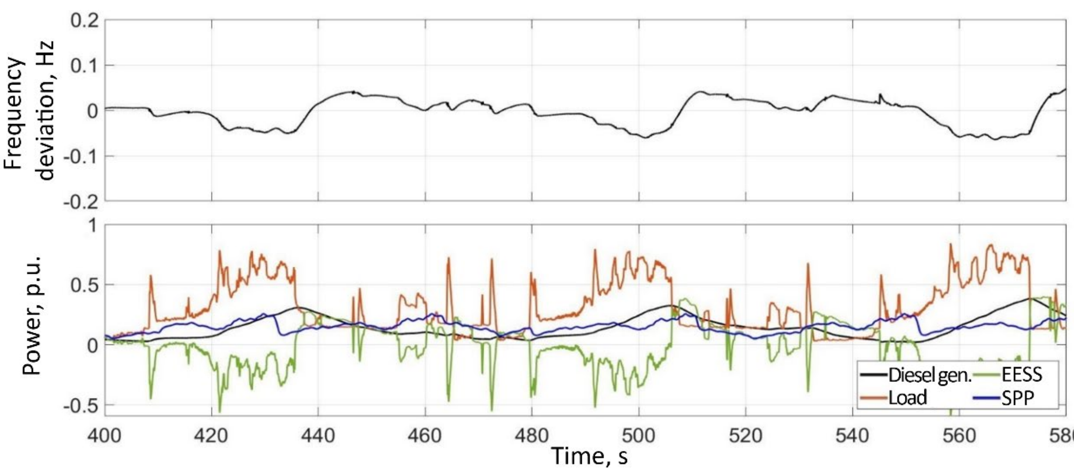

Figure 15 – Transient process during operation of the configuration No. 4 with the crane as a load

A comparison of configurations No. 1 and 2 shows that it is possible to improve the quality of electricity by optimizing the diesel generator speed controller, even without additional resources. However, the involvement of EESS and SPP (configurations No. 3 and 4) improves the power quality by an order of magnitude, which is important for sensitive electrical receivers or generators. The EESS and SPP have a short response time, and developed control system maximizes this advantage. Calculations show that optimization of all controllers decreases the maximum frequency deviation by 37% (when working with the crane load schedule) compared to the case when only the EESS and SPP controllers are optimized. But even without optimizing the parameters of the diesel generator speed controller, optimization of the EESS and SPP controllers provides a frequency deviation not exceeding 0.2 Hz, which is significant because in practical terms it is not always possible to change the parameters of the diesel generator controller.

It should be noted that when optimizing the parameters of the EESS controller, a value of the exchange energy intensity was obtained equal to 0.5% of the nominal energy intensity, determined by the main function of the EESS – the coordination of stochastic graphs of solar generation and load. Such a small value of energy intensity for engagement in frequency control almost does not affect the performance of EESS of its main function and the battery life.

5. CONCLUSION

Electrical energy storage systems are able to be fast-acting tools for frequency control. It is especially relevant for off-grid power systems. To use the benefits of the EESS, an appropriate automatic control system is necessary. To compose the requirements for it, the analysis of the results of monitoring in the drilling rig power system was carried out. During the 96-hour interval, more than 100 load throws with a magnitude greater than 30% (including above 70%) of the rated power were detected. The frequency deviation exceeds 1 Hz repeatedly, the maximum deviation reaches 3.41 Hz, which does not contradict the requirements of GOST 32144, but leads to negative consequences for the consumer equipment and generator sets. Thus, owners of power facilities often set stricter frequency limits than GOST. In accordance with the formulated requirements for the frequency control system, in order to ensure its effectiveness in off-grid power systems with sensitive consumers and generators, the maximum frequency deviation should not exceed 0.2 Hz. To develop control algorithms, a model of an off-grid power system with a diesel generator, EESS, SPP and a load were created in the MATLAB/Simulink.

A method of frequency control in off-grid power systems using EESS was proposed. It combines control by disturbance and frequency deviation and eliminates shock frequency changes, especially dangerous for sensitive electrical equipment. It also reduces frequency deviations to the level set in the United Power System of Russia. An algorithm was developed for the distribution in time of the involvement in regulation of different storages as parts of a hybrid EESS to save the resource of accumulators. An algorithm was developed for automatic maintenance of the charge level of storage by correcting the control action depending on the current state of charge. A concept of an automatic frequency control system in a power system with an autonomous hybrid power plant was proposed. It uses the capabilities of EESS and fossil fuel generation, creates a reserve of SPP power (when EESS cannot be involved in regulation) and distributes the control actions between EESS and SPP depending on the current charge level. A procedure for selecting the parameters of frequency controllers based on optimization was proposed.

The effectiveness of control algorithms was approved by simulation based on a mathematical model of an off-grid power system with load diagrams according to GOST IEC 60034-1 and abruptly variable energy consumption schedule of an industrial facility. When the EESS is involved in regulation, the maximum frequency deviation (depending on the considered load graph and the parameters of the diesel generator controller) ranges from 0.045 to 0.137 Hz. This is an order of magnitude better than the values when control is performed only by means of the diesel generator (maximum deviation from 1.038 to 4.533 Hz). Due to the algorithm for maintaining the charge level and a small value of the energy intensity involved in control, the engagement of EESS in regulation does not require additional capital investments. The quality of control satisfies the individual requirements of electric consumers sensitive to frequency deviations and allows to expand the field of application of AHPP and gas piston generators in off-grid power systems with an abruptly variable load.

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