Fuel Saving And Electric Power Quality Improvement In Autonomous Power Supply Systems By Using Energy Storages

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Abstract. In autonomous power supply systems for diesel power stations located in remote areas, the main component of costs is the cost of imported fuel. The use of energy storage systems reduces fuel consumption for an autonomous power station. Reducing the northern import of liquid fuel is a relevant task for Russia. The organization of the charge-discharge process of an energy system storage according to the criterion of the minimum daily fuel consumption depends on both the load schedule and the type of flow rate characteristic of the primary engine. When making design and investment decisions on the feasibility of using alternative technical solutions for the modernization of sources in isolated energy supply systems, a comparative assessment of their economic efficiency is necessary. The paper studies the choice of energy storage system power in terms of fuel economy, reducing the installed capacity of a power station for electric power supply systems.

1 Introduction

The use of energy storage systems (ESS) may be appropriate for diesel-generator units, primarily diesel fuel, gasoline, fuel oil, as their operation is associated with the need for constant delivery of fuel and its seasonal storage, with the need to work in intermittent modes following the load of consumers, which significantly increases fuel consumption, and, consequently, current costs [1-3]. To assess the economic efficiency of the designed facility, it is necessary to compare the capital (investment) costs of creating an electrotechnical complex (ETC) and the current costs of its operation. As a rule, for a quick project assessment at the stage of feasibility studies, the static method is used and the project payback period is calculated. The combination of ESS with an autonomous generator assumes solving a number of issues related to the optimization of the parameters of the created "generator-ESS" ETC. Battery Energy Storage Systems (BESS) are capable of damping power imbalances for short and long periods of time, storing large amounts of energy. As an example, it is possible to note that the General Electric Corporation and the California-based energy company Southern California Edison announced the implementation of the first project in the world of a hybrid power station in which a gas turbine unit (GTU) works in conjunction with ESS [4-6]. Such an application will provide a solution to such problems as:
- increasing the limits of the dynamic stability of GTU with small values of the moments of inertia during accidents in the grid;

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- stable operation of the auxiliary system and the GTU excitation system due to the maintenance of the required voltage level at the GTU clamps with significant voltage fluctuations in the network during autonomous GTU operation.

But, as you know, power units - electric generator drives for autonomous small thermal power plants, apart from GTU, can be diesel-generator units (DGU), gas piston installation (GPI). The determining criteria for the selection of power units for use in an autonomous power supply system (APSS) are fuel consumption issues, the level of operating costs, and the payback period of power station equipment. In addition, when choosing power units, factors such as ease of operation, the level of maintenance and repair, and also the place where the power units are to be repaired should be taken into account. These issues are primarily associated with costs and problems that may arise during the operation of an APSS. The tasks of ensuring the stabilization of the GPU rotation speed and optimal control of the ESS charge-discharge process should be worked out.

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2 The cycle of charge-discharge of the battery without taking into account energy losses

One of the problems that can be solved by applying the ESS based on electric batteries is fuel economy. Other problems solved by ESS are presented in [7–9]. The organization of the charge-discharge process of an ESS according to the criterion of the minimum daily fuel consumption depends on both the load schedule and the type of flow rate characteristic of the primary engine. Fig. 1 shows the relevant data for various types of engines, covering almost all types of flow characteristics.

Consumption characteristics 1 and 3 (Figure 1) are qualitatively the same. They are distinguished only by the fact that for diesel power stations the passport values of fuel consumption for a 25% load are given.

From Fig. 1 it is seen that a decrease in the generated power leads to an increase in specific fuel consumption. Thus, it is possible to provide a fuel economy in the "generator-ESS" ETC if the load schedule is substantially irregular. Then, during the minimum load hours, the BESS is charged, and during maximum load hours, it transfers its energy to the grid, Fig. 2a, graph 3, corresponding to the battery charge at constant current.

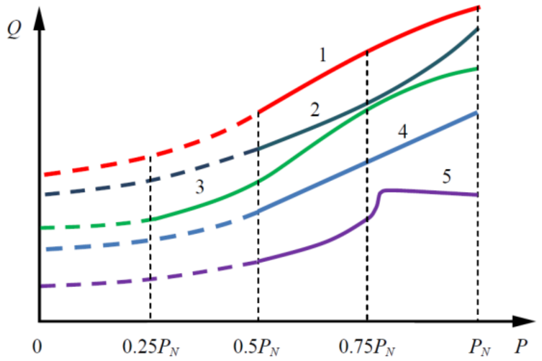

Fig. 1. Fuel consumption for various types of primary engines: 1 – Caterpillar G3520C CHP and Caterpillar G3516; 2 – MTU Onsite Energy 16V4000L33FN, (Diesel Fuel) – TSS TDS6606 LTE and Caterpillar G3516 DP158 LD; 3 – Perkins 4012TESI and Generac Pramac GGW300G; 4 – Cummins QST30G4 and Mitsubishi S12U-PTA; 5 – Perkins 400GT AG2A.

In this regard, the electric batteries are charged at the same power, Fig. 2a, with a variable load schedule. Moreover, the charge energy in the daily cycle is completely consumed during its discharge.

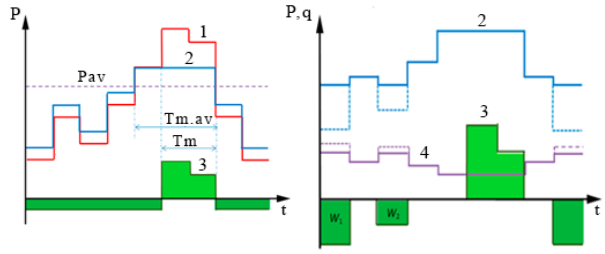

Fig. 2. Daily power and specific fuel consumption profiles: a - load power profiles (1), generator (2), ESS (3); b - power profiles and specific fuel consumption (4).

When optimizing the operation of a power station, the values of power losses at the first stage of development of the technique are not used. In this regard, a simpler method can be applied: either prescriptively assign the maximum duration, as is done in Fig. 2a, or calculate the average load on the daily time interval (Pav, Fig. 2a) and its part that is above the average, be attributed to the maximum load. This will highlight the interval of the duration of the maximum load Tm.av, Fig. 2a. In Fig. 2b shows an optimized BESS charge graph. It is formed on the basis of the laws of increasing specific fuel consumption with decreasing load. In order to reduce the daily fuel consumption, it is necessary to organize the recharging of the BESS in such a way as to maximize the GPU power generation during the day.

For definiteness, we assume that the characteristic of the specific fuel consumption of a power station (1) has the form [10]

$$Q_0 = Q_{nL} + bP^{\mu} \tag{1}$$

where Q_{nL} is the idle fuel consumption; b, μ are the approximation parameters, and $0 < \mu \leq 1$.

In [8, 9], the derivation of the formula is described which shows that for the optimal operating mode of the installation with a constant load, we obtain fuel consumption (2)

$$Q_{опт} = Q_{nL}T + (1{,}4)^{\mu} q P_{L1}^{\mu} T \tag{2}$$

In the case when ESS is not used, we have (3)

$$Q = Q_{nL}T + q\left(P_{L1}^{\mu} * 0{,}9T + 5^{\mu} P_{L1}^{\mu} * 0{,}1T\right) = Q_{nL}T + \left(0{,}9 + 5^{\mu}\right) q P_{L1}^{\mu} T. \tag{3}$$

The specific monetary effect of the use of ESS depends on the specific values of the coefficients of the expenditure characteristic.

3 Comparative economic efficiency of the energy storage system in combination with traditional sources of generation

When making design and investment decisions on the feasibility of using alternative technical solutions for the modernization of sources in isolated energy supply systems, a comparative assessment of their economic efficiency is necessary. As a basic variant of power supply:

option 1 was adopted - Power supply using Caterpillar 3512 DGU with a rated power of 1020 kW [13].

The following two technically feasible options have been adopted as alternatives:

option 2 - Power supply using a Caterpillar 3412 DGU with a rated power of 720 kW [4] in combination with a Liotech LT-LFP 700P ESS with a total power of 329 kW and a battery capacity of 3500 Ah, consisting from 5 modules in every 147 batteries [13; 14];

option 3 - Power supply with the use of Caterpillar G3516 GPU, with a rated power of 1030 kW in combination with Liotech LT-LFP 700P ESS with a total capacity of 329 kW and a battery capacity of 3500 Ah, consisting from 5 modules in every 147 batteries [13; 14];

A GPU with a rated power of 1030 kW was selected for greater clarity when comparing options, which is shown in Table 1 (in reality, it would be possible to install a GPU of lower power Caterpillar G3512 at 725 kW and, therefore, cheaper).

To assess economic efficiency, it is necessary to have data on capital investments in the scheme under consideration, exchange rates, technical specifications and the number of hours of use of the equipment, as well as on the consumption and cost of the fuel used.

The recommended GPU life cycle is 30–40 years [15; 16], DGU - 20-30 years, the battery life depends on various factors.

The capital investments necessary for the implementation of each of the options are shown in Table 1. Construction and installation work includes the cost of building the foundation of the generating installation, access roads, installation and commissioning, rental of construction equipment, and payment of wages to builders.

Table 1. Models and manufactures of fault indicators.

Parameter Name	Opt. 1	Opt. 2		Opt. 3	
	DGU	***DGU***	***BESS***	***GPI***	***BESS***
Rated power, kW	1020	720	329	1030 / 725	329
Capital expenditures for equipment (Keq), thousand euros	309.4	135.8	908.9	319.6/ 260.1	908.9
Capital expenditures for construction and installation works (Kci), thousand euros	24.7	10.8	72.7	25.5/ 20.8	72.7
Capital costs for transport and logistics services (Ktl), thousand euros	18.5	8.1	54.5	19.7/ 15.6	54.5
Total costs in ETC (Kes = Keq + Kci + Ktl), thousand euros	352.7	154.8	1036.2	364.4/ 296.5	1036.2

As can be seen from Table 1, the largest amount of capital investment corresponds to option 3 using GPI in combination with ESS. This is explained by the significant costs of both the purchase of the installation itself and the ESS included in the ETC as a BESS, as well as the costs of design and construction, work. Due to the high cost of ESS, the total capital costs in options 2 and 3 are significantly higher than in option 1 without ESS.

Maintenance and repair costs are calculated individually for each type of equipment. For DGU and GPI, the maintenance costs are determined depending on the number of operating hours of the equipment, in addition, the costs associated with changing the oil, filters, checking the condition of the fastening and electrical connections, checking the instrumentation and indicators on the control panel, etc. must be taken into account. [15, 16, 17].

The next step is the assessment of current costs for different operating modes of the installations. Table 2 presents the technical specifications from manufacturers for fuel consumption Q for DGU and GPI, as well as specific fuel consumption q.

Table 2. Fuel Consumption for DGU and GPI.

The degree of utilization of installations from the nominal,%	DGU (1020 kW)		DGU (720 kW)		GPI (1030 kW)	
	Q, l/hour	*q, l/kWh*	*Q, l/hour*	*q, l/kWh*	*Q, m^3/hour*	*q, m^3/kWh*
100	271.6	0.272	171.8	0.264	351.0	0.351
75	209.6	0.279	128.9	0.264	316.0	0.421
50	147.6	0.295	86.0	0.265	282.0	0.564
35	110.3	0.315	63.0	0.277	218.3	0.624
20	72.4	0.362	46.8	0.360	155.8	0.779
5	33.9	0.679	26.4	0.812	93.3	1.867

The table shows that with a decrease in the load on the generator in all three cases, the specific fuel consumption begins to increase, therefore, it is advisable to load the generator throughout the day from 50 to 100%.

For reference: the isolated power system of Kamchatka is 50% energy-efficient (at peak loads). This means that for a significant part of the time, electrical units operate in a mode with increased fuel consumption. In the no-load operation, fuel consumption is reduced by 70-80% of the "peak load" mode.

The number of hours of using the maximum load of consumers shows how many hours a year a consumer could work with the maximum load for a given annual power consumption (C^n_{year}) [14]: for oil refining h^n_{max} = 6000 - 8000 hour / year, for non-ferrous metallurgy or oil production h^n_{max} = 7000 - 7500 h / year, for ferrous metallurgy h^n_{max} = 6500 h / year, for machine building h^n_{max} = 3500 - 5000 h / year, for light industry h^n_{max} = 3000 - 4500 h / year.

With such a number of hours of work per year, the main component in the total costs is fuel costs. In general, the regions of the "northern delivery" have an extremely high price for imported fuel: it varies from 0.72 to 1.44 thousand euro/ton (for comparison: the cost of diesel fuel for consumers in the central part of Russia is approximately 0.66 thousand euros/ton) [18]. The share of the transport component in the price of fuel at the final consumer reaches 30-90% [16; 19]. In Yakutia, the average price of diesel fuel on the "northern delivery" in 2016 was 0.92 thousand euro/ton [20, 21]. The price of Arctic diesel fuel consumed by DGU, taking into account delivery to remote rural settlements - 1.14 euro/liter [22]. The cost of associated petroleum gas (APG) production is up to 3.60 euro, the price of such gas on the market is set at no more than 7.21 euro [23].

To calculate and compare fuel costs for DGU and GPI, it is necessary to bring them into a comparable form, bringing everything to one unit of measurement. Rostekhnadzor established its average fuel density coefficients for converting liters to tons, including diesel fuel - 830 kg/m3. For GPI, it is necessary to convert m3 into tons, taking into account the fact that APG is used for GPI, which consists of 22 components of the gas mixture, among which the main four are methane, ethane, propane, butane, their content, and density of natural gas and for APG, are presented in Table 3.

Table 3. The composition of APG oil field.

Gas mixture components	Component designation	Density according to GOST 2939—63, kg/m3	Natural gas, content in%	APG, content in%
Methane	CH_4	0.656	94.3442	61.7452
Ethane	C_2H_6	1.26	2.9114	7.7166
Propane	C_3H_8	1.8641	0.4312	17.5915
Butane	C_4H_{10}	2.48	0.0719	4.8729
Other gases	C_5H_{12}, C_6H_{14} C_6H_6, C_7H_{16} and 14 more components	0.98	2.2413	8.0738

Thus, based on Table 3, knowing the composition of the gas mixture and the density of its components, we determine according to the mixing rule the average density of the mixture (4):

$$P_n = \frac{\left(P_1V_1 + P_2V_2 + \ldots\ P_nV_n\right)}{100} \quad (4)$$

where P1, P2 ... Pn is the density of gas fuel components, kg/m^3; V1, V2 ... Vn - content of components, volume in percent.

Thus, according to formula (4), the average APG density will be 0.9463 kg/m^3. Thus, using the obtained average fuel density, we translate everything into tons of standard fuel, the total fuel costs per year are calculated by the formula (5) and are summarized in Table 4 at T_{max}=2628 h and T_{min}=6132 h for DGU and GPI:

$$C_T = Q_T \cdot F_T, euro \quad (5)$$

where Q_T is the annual fuel consumption, ton; F_T is fuel cost, euro/ton.

Table 4. Fuel costs per year.

Name	DGU (1020 kW)	DGU (720 kW)	GPI (1030 kW)
F_T, euro/ton	1380	1380	13.66
Q_T, ton	1 325.24	1110.93	2 474.92
C_t, thousand euro	1 829.6	1 533.7	33.8

This table does not take into account the costs of replacing oil, spare parts, maintenance, etc., however, they are not significant (about 10% of all costs), and the main share (about 90%) of all costs are fuel costs.

From Table 4 it can be seen that the highest annual fuel costs are observed when using DGU (option 1) when using an ESS and choosing a smaller DGU (option 2), fuel costs are reduced by 295.9 thousand euro while ensuring that the same load under the same conditions during the operation of the GPI (option 3) will require 33.8 thousand euro. This difference in fuel costs is due to the fact that APG is used for GPI, which is released during the production and preparation of oil. DGU, as a rule, operate at moderate and low installed capacity utilization factors, i.e., when equipment is not loaded enough and seasonal and daily energy consumption schedules typical for our country are insufficient, while DGU minimum fuel consumption is provided only at rated load. In addition, the GPI has several advantages over DGU:

GPI oil consumption: 330 g/MWh oil change after 2000 moto hour (220 l) - significantly lower than that of DGU, for which the flow rate is from 400 g/MWh. and a replacement period of 600 moto hour;

The term for an overhaul of the DGU requires overhaul through 30-45 moto hour, and GPI on average - after 60-80 moto hour;

An additional advantage of the GPI is the possibility of heating the premises: along with electric energy, you can get 1000 kW of heat every hour for heating.

Since the compared options differ significantly in terms of capital and current costs, the most preferred option is selected based on the calculation of the payback period of additional capital investments, which is determined by formula (6) as the ratio of their size to savings from lower operating costs:

$$T = \frac{K_2 - K_1}{C_1 - C_2} \qquad (6)$$

where K1, K2 - investment in the compared options; C1, C2 - operating costs for the same options.

The value of T shows the period of time during which additional capital costs are covered by savings on operating costs. By combining the options and comparing the calculated values with each other, the optimal option is determined with the minimum value of the calculation period.

The additional costs in option 2 with ESS will pay off due to fuel economy for 3 years. For option 3, the cost of annual gas consumption does not exceed 34 thousand euro, which makes this option uncontested in the presence of APG.

When choosing an ESS to ensure the stable operation of the GPI, it is important to coordinate the power of the ESS with the dynamic characteristics of the GPI. The power of the ESS will determine the dynamic mode, and the capacity will determine the graphs of the load.

4 Conclusions

The use of ESS in combination with a generating unit allows you to save fuel by optimizing the operating mode of the drive motor. For maximum fuel economy in the daily cycle, it is necessary to have preliminary information on the load schedule. This implies the advisability of forming a research direction in terms of automatically storing power profiles and optimizing the operation of ESS. Given the high cost of ESS, it is necessary to develop a line of the nominal power of ESS with a clear link to the characteristics of load schedules.

To make a decision on investing in a project and using a DGU, a DGU with ESS or GPI with ESS, it is necessary to consider the values of all the above parameters. GPI is advisable to apply with a significant need for electrical energy. Fuel for them is very cheap if it is possible to use APG. Despite significant capital investments in the application of GPI, its reliable operation during operation in combination with ESS provides a gain in the total accumulated costs from possible emergency situations, which allows us to recognize this option of energy supply as the most effective. Operating costs for GPI with ESS are significantly lower.

The possible reduction in the installed capacity of both DGU and GPI concomitant with the ESS installation should be evaluated comprehensively, comparing investments with current operating costs: more powerful power installations usually have a lower specific fuel consumption in the load range of 40-60% than those operating with a load 60 –100% less powerful power installations.

When choosing ESS to ensure the stable operation of the GPI, it is important to coordinate the power of the ESS with the dynamic characteristics of the GPI. power of the ESS will determine the dynamic mode, and its capacity will determine the graphs of the load. The introduction of ESS will contribute to the differentiation of power supply schemes and a general increase in energy efficiency.

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