Utilization of electrochemical energy storage devices in autonomous power supply systems

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Abstract. Diesel and gas piston power units are used as a source of electrical power in autonomous power supply systems. For diesel power plants located in remote areas, the main component of the costs are the cost of imported fuel. For gas piston power plants operating on associated gas, the main problem is to ensure the stabilization of the frequency of alternating current with sudden load changes. The use of electrochemical electricity storage devices as part of power plants largely solves these problems. The article considers the choice of storage capacity for fuel economy, reduction the installed capacity of a power plant and frequency stabilization in the power supply system. It is shown that for diesel power plants, the use of electrochemical accumulators leads to both fuel savings and a decrease in its nominal capacity. For gas piston units, where the specific increase in fuel decreases with increasing load, the use of electrochemical accumulators reduces the installed power, but increases fuel consumption. The accumulator parameters for gas piston units are determined by the allowable overload/discharge of the load, and according to the energy intensity, they are determined by the duration of the maximum load, which is smoothed by the drive operation. We present numerical examples for estimating fuel consumption taking into account the efficiency in the charge-discharge processes of storage batteries. The simulation models show the impact of the electrochemical storage device on the stabilization of the frequency of an autonomous electric power supply system.

1. Introduction

The modern architecture of the Russian electric power industry is a combination of centralized power supply from large power plants with powerful units (over 200 MW) connected by high-voltage main power grids of 220 kV and more, with power supply to consumers from local power systems with distributed generation with low-capacity power plants. According to the expert estimates, the share of distributed generation accounts for about 5-10% of the total electricity generation in Russia, and the total installed capacity of small power plants is 12-17 GW [1]. At the same time, the tendency of consumers to move away from centralized energy supply to their own generation and the development of distributed energy in recent years is increasing. The main factor contributing to the change in the technological paradigm is the growing inefficiency of the Russian electricity sector due to the exhaustion of the growth potential of centralized energy systems and the lack of real competition in the retail market, leading to an increase in tariffs and electricity prices for consumers. Therefore, in cases where distributed energy has an advantage, it should be used.

The Russian Federation is the largest state in the world in terms of the area of decentralized power supply zones, in which consumers are independently supplied by power, i.e. regardless of the centralized network, when electricity is generated exclusively by domestic sources. These include the Far East, the...
Arctic zone, the Far North regions, where distributed generation facilities are introduced. These autonomous power supply systems can become growth points of the small energy sector.

The interest in the use of energy storage devices in electric power systems has sharply increased. This is explained both by the trends in the development of generating capacities and by new technologies of energy storage devices production based on high-power accumulator batteries (HPAB). A significant expansion of their economically feasible application is expected, which is driven by the global progress in the field of operational characteristics of chemical batteries (in particular, lithium-ion batteries), as well as due to the outlined dynamics of their cost reduction, as a result of electric vehicles use in the near future, [2-11].

When choosing the installed capacity of the power plant and the HPAB power harmonized with it, it is necessary to take into account that the majority of autonomous power supply systems have a highly non-uniform load schedule, and for industrial power supply systems, one should take into account its possible fast-changing nature. In the absence of HPAB, the capacity of autonomous power plants, both for diesel power plants (DPP) and power plants based on gas piston units (GPU) is selected by the maximum load. In this case, the average load power is, as a rule, significantly less than the installed power of the units.

2. Utilization of storages to reduce the capacity of power unit

HPAB utilization in power plants [9–11] with DPP makes it possible to smooth power deviations from the average value. This results in the possibility of reducing the installed power of the DPP to the average load and, at the same time, can lead to fuel savings. The latter is fundamentally important for DPP, since it requires the delivery of liquid fuel.

Optimization of the HPAB charge-discharge process according to the criterion of the minimum daily fuel consumption $Q_s$ depends both on the load chart and on the type of the flow characteristic of the prime mover. Tables 1 and 2 show the corresponding data for various types of engines, covering almost all types of consumption characteristics, Figure 1.

![Figure 1. Fuel consumption for various types of primary engines](image)

1 - columns 2, 3, table 1; 2 - column 6, table 1, columns 5 and 8, table 2;
3 - columns 4 and 5, table 1; 4 - columns 2, 3 and 4, table 2; 5 - columns 6 and 7, table 2.
Table 1. Gas consumption in the GPU at various loads.

| Engine          | Caterpillar G3520C CHP | Caterpillar G3516 | Perkins 4012TESI | Generac Pramac GGW300G | MTU Onsite Energy 16V4000L33FN |
|-----------------|------------------------|-------------------|-------------------|-------------------------|-----------------------------|
| Fuel consumption per hour | $Q_1$, m$^3$ | $Q_2$, m$^3$ | $Q_3$, m$^3$ | $Q_4$, m$^3$ | $Q_5$, m$^3$ | $Q_6$, m$^3$ |
| 100% load       | 518                    | 279               | 186               | 57.1                    | 429                         |
| 75% load        | 400                    | 219               | 144               | 45.1                    | 329                         |
| 50% load        | 279                    | 155               | 96                | 33.3                    | 231                         |
| 25% load        | ---                    | ---               | 51                | 21.5                    | ---                         |
| Rated power, kW | 2000                   | 1030              | 600               | 240                     | 1718                        |

Table 2. Liquid fuel consumption in the DPP at various loads.

| Engine          | Mitsubishi S12U-PTA | Perkins 4012-46 TWG2A | Cummins QST30G4 | TSS TDS 660 6LTE | Perkins 400GT AG2A | Perkins 2806C- E18TAG2 | DP158 LD |
|-----------------|---------------------|-----------------------|-----------------|-----------------|--------------------|-----------------------|----------|
| Fuel consumption per hour | $Q_1$, l | $Q_2$, l | $Q_3$, l | $Q_4$, l | $Q_5$, l | $Q_6$, l | $Q_7$, l |
| 100% load       | 586.5               | 291.9                | 201.3           | 161.1           | 149.8              | 116                     | 127.8 |
| 75% load        | ---                 | ---                  | ---             | ---             | 155                | 118.4                  | ---     |
| 50% load        | 440                 | 219                  | 151             | 119.1           | 112.4              | 87                     | 91.1    |
| 25% load        | 293.5               | 146.1                | 100.7           | 79.3            | 75                 | 58                     | 60.9    |
| Rated power, kW | 2308                | 1000                 | 800             | 600             | 582                | 480                    | 422     |

Consumption characteristics 1 and 3, Figure 1, are qualitatively the same. They are distinguished only by the fact that for diesel power plants passport fuel consumption are given for a 25%-load.

Minimization of fuel consumption in the daily cycle of the autonomous power plant is associated with the use of HPAB. For consumption characteristics of type 2 in relation to a two-stage load schedule (minimum power $P_{L1}$, maximum power $P_{L2}$, maximum duration $T_m$), the condition for minimizing fuel consumption [12] and, accordingly, the condition for selecting the power HPAB is equal to

$$\frac{1}{\eta} \frac{\partial Q_1}{\partial P_1} = \eta \frac{\partial Q_2}{\partial P_2},$$

(1)

where $\eta$ is the efficiency of the process of HPAB charge-discharge, $P_1$ is the generated capacity of the power unit during the minimum load hours, $P_2$ is the capacity of the power unit at the interval $T_m$.

If we assume that the consumption characteristic is of the form [12]

$$Q = a + bP^\mu,$$

(2)

then from the conditions of the energy balance of the storage and power unit during the day $T$ in the “charge-discharge” mode taking into account formula (2) we obtain

$$P_2 = \frac{P_{L1} + \rho P_{L2}}{\eta^{2/\mu - 1} + \rho} = \frac{k_m P_{L2}}{\eta^{2/\mu - 1} + \rho},$$

(3)

where $\rho = \chi/\eta^2$, $k_m = P_{L2}/P_{L1}$, $\chi = T_m/T - T_m$,

and from the condition (1) we get

$$R_1 = \eta^{2/\mu - 1} P_2.$$

(4)
Equations (3) and (4) allow one to choose the optimal capacity of power unit and the corresponding minimum HPAB capacity.

Consider for example the column 6 of table 2. For it in expression 5 we assume \( \mu = 1.45; a = 22.31; b = 368.57 \). Let \( P_{L2} = 0.4 \text{ MW}, k_m = 5, \eta^2 = 0.9 \), and \( \chi = 0.2 \); so \( \rho = 0.222; \eta^2/\mu - 0.791 \). If DPP will operate without storage, then \( P_2 = 0.2 \text{ MW}; P_3 = 0.4 \text{ MW} \) and
\[
Q_s = a^*T + b[(P_1)^m*(T-T_m) + (P_2)^m*T_m] = 1115.1 \text{ l.} \tag{5}
\]
If there is a storage in accordance with formulae (3) and (4), we get: \( P_1 = 0.1318 \text{ MW}, P_2 = 0.1666 \text{ MW}, Q_s = 1035.4 \text{ l.} \) At the same time, it is sufficient to have the power unit of capacity which is two times less than the rated power of 200 kW. HPAB power will be about 260 kW.

For a GPU with a consumption characteristic of type 1, the use of energy storage devices, as well as for DPP, makes it possible to reduce the rated power, but at the expense of increased fuel consumption. Consider the consumption characteristic of a GPU, column 2, table 1, assuming it to be convex over the entire range of load variation. Calculations show that in this case, \( \mu = 0.96; a = 23.5; b = 254.2 \). Then for \( \eta^2 = 0.9; \chi = 0.2 \); and \( k_m = 5 \) (2 MW/0.4 MW) we get \( Q_s = 4903.2 \text{ m}^3 \). In the absence of the drive \( Q_s = 4651.5 \text{ m}^3 \).

3. Utilization of storages to maintain frequency in an autonomous network.

For the GPU, an important point is the use of storages to stabilize the frequency in an autonomous electric network during load surge and shedding. Figure 2 shows a diagram of a GPU MTU 8V4000L32 with a rated power of 776 kW. It presents the maximum load surge/shedding for a given base power, subject to ISO 8528-5, according to which the frequency deviation range of +18/-25% is allowed for the G1 generator class (frequency recovery time is 10 s), and for the G3 generator class the allowed range is +10/-15% (frequency recovery time is 3 s).

\[
\begin{array}{c|c|c|c|c|c}
\hline
\Delta P, \% & 0 & 10 & 20 & 30 & 40 \\
\hline
P, \% & 0 & 10 & 20 & 30 & 40 \\
\hline
\end{array}
\]

**Figure 2.** Diagram of permissible loads for the GPU MTU 8V4000L32.

In the presence of an industrial electromotive load in the start and stop modes of electric motors, there may be significant differences in the load from the allowable values given by the diagram. So, when running a GPU with a load of 13% to 94%, it is permissible to stepwise connect no more than 5.8% of power, which is only 45 kW, and for a GPU loaded to 70%, a load drop of 3.2% is acceptable, i.e. 24.8 kW.

The use of electrochemical drives as a part of GPU solves the problem of their sensitivity to a step change in load. Figure 3 shows the results of a GPU modeling in the absence of storage and various
impacts from the load side. Figure 4 shows the simulation results for a 1000 kW GPU operating in stepwise load change modes when using a storage.

**Figure 3.** Changing the parameters of the electrical network in the circuit without a current source.

- \( f \) is the current frequency, Hz;
- \( I_{sm} \) is the effective value of the generator current, A;
- \( I_n \) is the effective value of the load current, A.

**Figure 4.** Changing the electrical network parameters in the scheme with controlled current source:

- \( f \) is the current frequency, Hz;
- \( I_{sm} \) is the effective value of the generator current, A;
- \( I_n \) is the effective value of the load current, A;
- \( I_i \) is the effective value of the current source current, A.

The short-term discharge of a storage onto a network during load surge and its corresponding charge during load shedding, consistent with the characteristics of the initial drive, make it possible to use it with a relatively small capacity. Power of storage is determined by the load surge.

### 4. Conclusions

Load surges and sheddings occur both for the residential sector and for industry. Thus, boilers turn-on in the children educational institutions leads to an almost instantaneous increase in power by 20-40 kW, and turn-on of emergency ventilation by a fire alarm - up to 100 kW or more. Industrial loads lead to even greater stepwise power changes both during engine start-ups and in case of their emergency
shutdown by protective devices in loaded mode. For the successful application of gas piston units operating on associated gas, the frequency stabilization in an electrical AC network can be achieved by installing electrochemical accumulators on the corresponding currents of relatively low electrical intensity. At the same time, issues of fuel economy for them become secondary.

The use of associated gas in remote areas, for which the cost of imported liquid fuel increases many times and creates an additional environmental burden by its transport capacities, at gas piston units supplementation by electrochemical energy storage devices, has no alternative.

A possible reduction in installed capacity of both DPP and GPU associated with the installation of storage units should be assessed comprehensively by comparing investments with current operating costs: more powerful units have, as a rule, lower specific fuel consumption in the load range of 40–60% than working with the 60 — 100% load less powerful power units.

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