Modeling the process of redistributing power consumption using energy storage system with various configurations to align the electrical loads schedule

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Abstract. The paper considers issues related to the analysis and adjustment of electrical load schedules. The main characteristics of the load graphs are represented in this paper. The research deals with issues of possibility of aligning load graphs by using energy storage devices. The configuration of the storage system has been identified, which allows expanding its functionality. A logical-numerical model of a hybrid energy storage system has been developed. As a result of the simulation, dependencies are obtained that confirm the efficiency of using power storage devices to align the load schedules.

1. Introduction
One of the main indicators of energy efficiency of power supply systems are the graphs of electrical loads. The unevenness of the load schedules leads to an increase in losses in the production, transmission and consumption of electricity. Also, during peak hours, much more resources are spent on generating electricity than during periods of “failures”, and each shutdown and start-up of power units is associated with large overheads, thereby reducing the installed capacity utilization factor (ICUF) of power plants. Considering the stated above, equalization of the load schedule will make it possible to increase the ICUF and reduce the energy loss in the networks, which is the most important effect from the point of view of the power system [1, 2, 3].

2. Load graph analysis

![Figure 1. A typical schedule of active load: a) - daily, b) - annual](image)
It is necessary to distinguish between individual and group load schedules - respectively for individual power consumers and for feeders that feed groups of power consumers. When solving issues related to the adjustment of load schedules, mainly group reviews are considered, individual load schedules are important for understanding the physical picture of the formation of group schedules (Figure 1).

We consider the following indicators of load graphs:
- rms (effective) load for a given step-by-step graph
  \[ P_e = \sqrt{\frac{1}{n} \sum_{i=1}^{n} P_i^2}, \]  
  where \( P_i \) – active power for the period, \( n \) - the number of equal duration periods;
- average power
  \[ P_a = \frac{1}{n} \sum_{i=1}^{n} P_i, \]  
- form factor
  \[ K_f = \frac{P_e}{P_a} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} P_i^2 \left( \sum_{i=1}^{n} P_i \right)^2}, \]  
- utilization factor
  \[ \beta = \frac{P_{\text{min}}}{P_{\text{max}}}, \]  
  where \( P_{\text{min}} \) - night minimum consumption; \( P_{\text{max}} \) - daily maximum consumption. Obviously, the smaller the value of \( \beta \), the more uneven the load curve;
- fill factor or load density
  \[ \gamma = \frac{\sum_{i=1}^{n} P_i}{24 P_{\text{max}}^2}, \]  
  which is the ratio of daily electricity consumption to the maximum possible consumption.
- number of maximum load hours
  \[ T_{\text{max}} = \frac{\sum_{i=1}^{n} P_i}{P_{\text{max}}} = 24, \]  
- adjustable input power range
  \[ \Delta P_{\text{adj}} = P_{\text{max}} - P_{\text{min}}. \]
Considering stated above, the load graph can be divided into four zones with different densities: the baseline - below the night minimum, half-base and half-peak - between the day and night minimum and peak - above the day minimum.

Information about these indicators will allow you to determine the size of the cross-sections of the conductors of the supply cables, evaluate the losses in the networks, choose the power of the generators of power plants, design power supply systems for enterprises, and also solve issues related to the adjustment of load schedules.

3. **Load schedule adjustment**

Turning to the issue of adjustment the load schedule, one way is to use consumer regulators at industrial enterprises. According to G.S. Khronusov, a complex of consumers - enterprise power regulators, has a set of power consumers controlled by a single program in load adjustment mode with the aim of creating optimized schedules for electric loads of enterprises [4-7]. Powerful and highly automated equipment is used as consumption regulators. This helps to provide a significant reduction in load peaks. However, the use of load regulators is complicated by the fact that the daily power consumption schedules of the main energy systems of industrial enterprises of various industries began to be characterized by the presence of two, almost the same maximums, as shown in Figure 1. In this regard, the real effect of reducing the demand for power is possible only with a balanced decrease of morning and evening highs [8-10]. A more efficient use of consumption regulators is possible when using dual-rate and differentiated by day zones tariffs. However, with adjustment the consumption of large nodes, shift the load zones of the daily maximum. The applicable tariffs are fulfill their task, however, with adjustment the consumption of large nodes, the load of the daily maximum zone will shift. Such conditions lead only to the formation of new highs.

An alternative to the use of consumption power regulators is the use of energy storage. At the moment, a wide range of solutions has been developed. They built on various principles, differing in both technical and economic indicators, and functional purpose, among which, first of all, batteries and supercapacitors should be highlighted.

There are the following operating modes: electric power accumulation (charge), storage (buffer), electric power output (discharge), emergency (sharp discharges and load surges). In the energy storage mode, the storage is charging from excess electrical energy, which helps to avoid the termination of generating equipment. When the storage is used in buffer mode, the storage works on a par with other (main) sources of electricity. In discharge mode, the storage delivers stored energy to the consumer. In the event of emergency conditions, the accumulation allows damping power fluctuations, and both modern storages and energy sources have a high energy transfer rate, as well as high maneuverability, which provides power reversal.

In all the modes stated above, the power balance in the storage connection node must be observed as:

\[
\begin{align*}
    P_{\text{load}} & \pm P_{es} + P_{g} = 0; \\
    Q_{\text{load}} + Q_{fcd} + Q_{es} + Q_{g} &= 0. 
\end{align*}
\]

(8)

where \( P_{\text{load}}, P_{g} \) - active and reactive power loads and generations, \( P_{es} \) - active and reactive power consumed by the energy storage device, \( Q_{fcd} \) - reactive power of filter compensating devices.

The energy storage device must work for a time determined from the load schedule, so its working energy consumption is determined by the formula:

\[
E_{es,op} = \int_{0}^{t_{op}} P_{\text{load}}(t) dt, 
\]

(9)
where \( t_{op} \) - the energy storage operating time, which depends on the charge / discharge rate of the energy storage.

Full energy consumption of the storage (including emergency components):

\[
E_{es} = E_0 + E_{es,op} + E_{em},
\]

where \( E_0 \) - minimum level of accumulated energy, \( E_{em} \) - emergency power consumption of the storage for damping vibrations arising in any of the operating modes.

Thus, we distinguish four parameters of the energy storage device that determine its functionality:
- maximum power of the storage \( P_{es,max} \);
- full power consumption \( E_{es} \);
- runtime \( t_{op} \);
- power reverse time \( t_{rev} \).

Without a doubt, these parameters depend on the power supply system into which the energy storage device is being implied and, often, fulfilling all the requirements is impossible from a technical point of view, or installing the storage becomes economically inexpedient [11-13]. However, it is allowed to expand the functionality by the joint use of energy storages of various types: rechargeable batteries and supercapacitors. We note that hybrid storages, in contrast to storages consisting only of batteries, have the following advantages [14, 15]:
- the maximum power of the energy storage increases;
- the operating time of the energy storage device by reducing the effect of peak load on the batteries increases;
- power reverse time reduces, since supercapacitors have high speed.

Thus, the functionality of hybrid storages is much wider than that of storages consisting only of rechargeable batteries, which will allow hybrid storages to be integrated into almost any power supply system, while operating costs are reduced by increasing the battery life span.

4. Practical results

In order to confirm the effectiveness of adjustment of load schedules with the help of electric energy storage devices, we use the method described in the article [1]. The authors obtained a relationship between the value of the shape factor and the change in losses in the networks leading to the load node:

\[
K_{CHM} = 1 - \frac{I}{K_f^2}.
\]

This formula will allow you to quickly assess the change in losses in the power grid while aligning the load schedule. We consider the example of a daily load schedule of an industrial enterprise below.

We selected the previously described zones and calculated the indicators according to the formulas (1-7).

The calculated indicators of this load schedule graph (Figure 2) are presented in Table 1.

The above parameters were calculated for an electric energy storage device consisting of only one type of storage device (battery) and hybrid (battery + supercapacitor battery). We will use these parameters when modeling regulatory processes (Table 2, 3).

We simulate the process of adjustment load schedules using the modified BESS (Battery Energy Storage System) block to HESS (Hybrid Energy Storage System) in the Matlab Simulink software environment using calculated parameters and options [16]. The block is a logical-numerical model of charge / discharge controllers, bidirectional inverters, a battery block and a supercapacitor block (Figure 3).
Figure 2. Load schedule graph with dedicated zones

Table 1. The performance of the load schedule graph

| Parameter                        | Value  |
|----------------------------------|--------|
| Rms (effective) load, kW         | 366.78 |
| Average power, kW                | 344.83 |
| Form factor                      | 1.063  |
| Utilization factor               | 0.26   |
| Fill factor or output density     | 0.57   |
| Number of hours of maximum load use | 13.7  |
| Adjustable input power range, kW | 440    |
| Conductor heating coefficient (maximum) | 0.11 |

Table 2. The energy storage device parameters (battery only)

| Storage parameter                | Value  |
|----------------------------------|--------|
| Maximum storage power, kW        | 100    |
| Full power consumption, kW * h   | 1260   |
| The initial charge level of the battery, % | 40    |

Table 3. Hybrid energy storage parameters

| Hybrid storage parameter         | Value  |
|----------------------------------|--------|
| Maximum storage power, kW        | 600    |
| Full power consumption, kW * h   | 1760   |
| The initial charge level of the battery, % | 40    |
| The initial charge level of the battery, % | 40    |
Figure 3. Hybrid storage system block

Trial 1. The load schedule adjustment using an energy storage device consisting only of rechargeable batteries (BESS) (Figure 4).

Figure 4. Load schedule graph before and after BESS adjustment.
Table 4. Parameters of the load schedule graph after adjustment with BESS

| Parameter                                | Value  |
|------------------------------------------|--------|
| Rms (effective) load, kW                | 357.06 |
| Average power, kW                       | 353.13 |
| Form factor                             | 1.01   |
| Utilization factor                      | 0.52   |
| Fill factor or output density            | 0.70   |
| Number of hours of maximum load use     | 16.78  |
| Adjustable input power range, kW        | 240.00 |
| Conductor heating coefficient (maximum)  | 0.02   |

Trial 2. Adjustment of the load schedule using a hybrid energy storage device, assembled of a battery unit and a supercapacitor unit (HESS) (Figure 5).

Figure 5. Load schedule graph before and after adjustment with HESS

Table 5. Parameters of the load schedule graph after adjustment with HESS

| Parameter                                | Value  |
|------------------------------------------|--------|
| Rms (effective) load, kW                | 348.34 |
| Average power, kW                       | 347.96 |
| Form factor                             | 1.0011 |
| Utilization factor                      | 0.86   |
| Fill factor or output density            | 0.91   |
| Number of hours of maximum load use     | 21.97  |
| Adjustable input power range, kW        | 50     |
| Conductor heating coefficient (maximum)  | 0.0022 |

5. Analysis

According to the results of trials, several conclusions can be drawn. Firstly, given the fact that the value \( K_{CHM} \) is significantly reduced as a result of the equalization of the load schedule, it can be argued about the effectiveness of the use of energy storage devices for these purposes.

Secondly, with the joint use of batteries and supercapacitors, results were obtained that prove the promise of their joint use, the load graph shape factor tends to 1, “jams” 2 and power dips are leveled.
due to the fast charge / discharge of the SC, and the value of the residual charge on the battery increases, which allows to extend the life cycle of the battery, preventing its complete discharge during operation.

Thirdly, the results of joint use of batteries and supercapacitors proves that such approach is highly effective. the load graph shape factor tends to 1, peaks and dips are leveled due to the fast charge / discharge of the battery, and the value of the residual charge on the battery increases. This helps to extend the life cycle of the battery, preventing its complete discharge during operation.

Fourthly, the work does not address the issue of the economic feasibility of introducing energy storage devices, however, given the fact that energy storage technologies are becoming cheaper every year, and electricity tariffs are constantly growing, the payback period of such projects will be reduced.

6. Conclusion
The questions considered in the work confirm the fact that to ensure a high coefficient of utilization of the installed capacity of power plants and reduce power losses in electric networks, rational and effective adjustment of load schedules is necessary, which, in turn, is possible only with a complete analysis of the source data, with the identification of all of the above indicators. In turn, the expansion of the functionality of modern energy storage devices, while lowering operating costs, as well as the effectiveness of their application in the formation of load schedules, contributes to their integration in almost any power supply system.

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