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The Use of Hybrid Energy Storage Devices for Balancing the Electricity Load Profile of Enterprises

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Abstract. In this article, the authors consider the possibility of using a hybrid energy storage system to even out the load profile of the enterprise. Solving the problem of rational use of energy storage taking into account the initial variable load schedule will significantly reduce not only the cost of electricity consumption by the enterprise, but also the costs of its production. Detailed characteristics of batteries with various types of electrolytes and supercapacitors are given. A model of the active scheme of a hybrid electric energy storage system consisting of a lithium-ion battery and a supercapacitor unit with the corresponding characteristics is presented. The model was carried out by using the SimPowerSystems software in MatLab. During the simulation, the temperature and the aging effects and of the batteries were not taken into account. The self-discharge parameter of the battery was also not presented. As a result of the simulation, discharge characteristics of supercapacitors and batteries were obtained based upon which the expediency of their combined use for leveling load profiles of various types was substantiated. The paper presents the results of the simulation of operating modes of a hybrid energy storage device, combining the advantages of two types of energy storage devices, as well as a diagram of delivered power to the network, corresponding to the specified parameters. The paper provides a mathematical description of the increasing power by hybrid storage system resulting from the combined use of supercapacitors and batteries. The paper presents the dependence of the power increase ratio on the frequency and the pulse current duty ratio, which proves that the maximum possible output power of the hybrid storage system can be several times greater than the power of a single battery having the same parameters.

Keywords: hybrid energy storage device, rechargeable battery, supercapacitor, electricity load profile, power consumption

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Применение гибридных накопителей электроэнергии для выравнивания графика нагрузки предприятий

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Реферат. В статье рассматривается возможность применения гибридного накопителя электроэнергии для выравнивания графика нагрузки предприятия. Решение задачи рационального использования накопителей энергии с учетом исходного переменного графика нагрузки позволит существенно снизить не только затраты на потребление электроэнергии предприятием, но и затраты при ее производстве. Приводятся подробные характеристики аккумуляторных батарей с различными типами электролитов и суперконденсаторов. Представлена модель активной схемы гибридного накопителя электроэнергии, состоящего из литий-ионной батареи и блока суперконденсаторов с соответствующими характеристиками. Модель разработана с помощью пакета прикладных программ SimPowerSystems в MatLab. При моделировании не учитывались температурный эффект и эффект старения аккумуляторных батарей, а также параметры относительно саморазряда аккумуляторной батареи. В результате моделирования получены характеристики разряда блоков суперконденсаторов и аккумуляторных батарей, на основании которых выявлена целесообразность их совместного использования для выравнивания графиков нагрузки различных типов. Представлены результаты моделирования режимов работы гибридного накопителя энергии, совмещающего достоинства двух типов накопителей энергии, а также получен график отдаваемой в сеть мощности, соответствующий заданным параметрам. Приведено математическое описание процесса увеличения мощности гибридного накопителя в результате совместного использования блоков суперконденсаторов и аккумуляторных батарей. Построен график зависимости коэффициента увеличения мощности от частоты и величины коэффициента заполнения импульсного тока, который показывает, что максимально возможная выходная мощность гибридной накопительной системы может быть в разы больше мощности одиночной батареи с такими же параметрами.

Ключевые слова: гибридный накопитель электроэнергии, аккумуляторная батарея, суперконденсатор, график электрической нагрузки, потребление электроэнергии

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Introduction

Due to the development of electric power systems, an increase in the capacities of power generating units, the issue of electric energy storage becomes more and more relevant. Since the electric load curve is one of the key indicators of the rational use of power supplied to the enterprise, it can be concluded that irregularity of this curve reduces the energy efficiency of power generation, transmission and consumption [1–5]. In order to implement each of these stages it is required to install expensive equipment with overestimated characteristics, which operates at its rated values only for a short time period.

Proceeding from the above, the development of an approach to the rational use of energy storage devices (ESD) taking into account the initial variable load curve will significantly reduce not only the costs associated with power consumption by the enterprise, but also the costs associated with power generation [6]. The most advantageous is the use of ESD in connection points with a sharply fluctuating type of load, in stand-alone power supply systems, in microgrids with nonconventional power sources [7–9] and in stand-alone power plants of the oil and gas sector [10, 11], with the majority of consumers having stochastic or periodically changing loads, the power of which is comparable to the power of generating units.

The existing modes of operation of electric energy storage devices are as follows: electric power accumulation (charge), storing (buffer), electric power output (discharge) and emergency (sharp load release and load rise).

Under conditions of the mode of power accumulation, the storage device is charged with excess electric power mainly when passing the “off-peak” load, which renders possible to avoid the generating equipment stopping. When operating in the buffer (“floating”) mode, the storage device works in parallel with another (primary) source of electric power. Under conditions of the discharge mode, the storage device delivers accumulated power to the consumer. In the event of emergency, the storage device allows one to damp power fluctuations, since modern electric energy storage devices have a high rate of power output to the network, as well as high maneuverability, which is characterized by the power reverse time t_{rev}, required to transfer it from the accumulation mode to the output mode, and vice versa [12, 13].

Being a multifunctional element of the energy grid, the energy storage device, in addition to controlling active power, can at the same time act as a reactive power control device, an active filter of higher harmonics [14–16], and also as a device for compensating the asymmetry of a three-phase voltage.

To date, a wide range of storage devices, based on various principles, has been created, characterized by different cost/performance parameters and purpose of use, among which, first of all, it is worth noting batteries and supercapacitors (ionistors). This paper presents a comparative analysis of the characteristics of these storage devices, considers special aspects of their operation, as well as the possibility of using a hybrid storage device for leveling the load curve of the enterprise.

Determination of the structure of a hybrid electric energy storage system

Storage devices of various types have been widely used in electric power systems of different countries, but nonetheless the most significant place among them is given to batteries. It is also worth noting that recently interest in electric energy storage devices has significantly increased owing to enhancement of works on the creation of intelligent electric power systems, wherein these devices act as one of the key elements. The principle of operation of a battery is based on the reversibility of chemical reactions [17]. Detailed comparative characteristics of batteries with various types of electrolytes are presented in Tab. 1.

Table 1

The comparative characteristics of batteries

Title	Capacity of unit, A·h	Energy density, W·h/kg	Number of charge/discharge cycles	Permissible charge temperature range, °C	Permissible discharge temperature range, °C
Lead Acid	26–3000	30–60	200–1200	–20–50	–20–50
Li–ion	40–800	80–160	700–3000	0–45	–20–60
NiCd	10–1100	45–80	1500	0–45	–20–65
Ni–NaCl	40–200	140–190	3000–7000	0–45	–20–65
NiMH	0,3–7	60–120	300–500	0–45	–20–65

Lithium-ion and nickel-cadmium batteries are the most widely used in industrial electric energy storage devices. These batteries are used, as a rule, under the buffer mode, i. e. are in a full charged state and at any moment are ready to accept the current load. The full charged state is maintained by constant or periodic recharging. However, they can also be operated under charge/discharge mode; therefore, it is advantageous to use these storage devices for leveling load fluctuations in energy grids within 24 hours. The disadvantages of the batteries include the high cost and their lifespan which directly depends on the number and pattern of "charge/discharge" cycles during operation. These characteristics are the main limiting factor, keeping these storage devices from widespread use. In addition, the paper [18] considers another factor, limiting the use of batteries, namely, the response time of the storage device. The response time of batteries makes up to 60 ms according to the Electric Power Research Institute (USA). This factor can have a significant impact when choosing an electric energy storage device, because there are some technological processes, wherein power supply shortage even for 20 ms is critical.

However, supercapacitors (SC) are virtually missing the above-mentioned disadvantages. Distinctive features of SC include the possibility of their quick charge an unlimited number of times and discharge within a time period varying from several milliseconds to tens of minutes, delivering high capacities to the load. It is advantageous to use this feature of SC under emergency operating modes of the electric energy storage device. The disadvantages and limiting factors of the use of SC include relatively low energy density and high self-discharge. It is also worth noting that the response time of SC makes from 1 μs. The characteristics of SC are presented in Tab. 2.

Table 2

Characteristics of supercapacitors

Title	Capacity of unit, F	Energy density, W·h/kg	Number of charge/ discharge cycles	Permissible charge temperature range, °C	Permissible discharge temperature range, °C
SC	500–12000	1–10	>500 000	–40–65	–40–65

Proceeding from the aforesaid factors, to date, it is advantageous to use batteries together with SC to compensate for the disadvantages and combine the advantages, to create hybrid electric energy storage devices (HESD) [13].

The paper [19] considers possible embodiments of the structure of a hybrid electric energy storage device in details. Taking into account the above-mentioned it can be concluded, that the most preferred embodiment for HESD circuit is an active circuit using two DC/DC converters.

Simulation modeling of the active circuit of a hybrid electric energy storage device

To substantiate the efficiency of the use of batteries together with supercapacitors, a simulation model of a hybrid storage device was developed, as shown in Fig. 1.

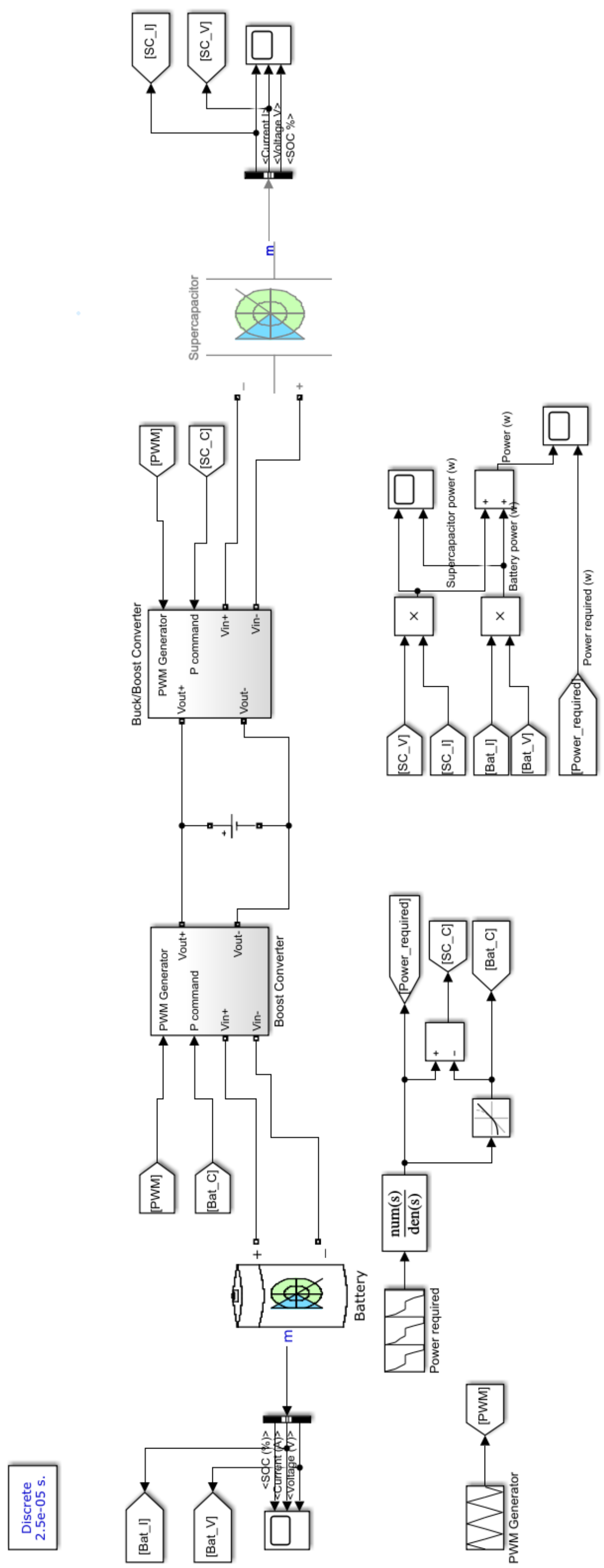
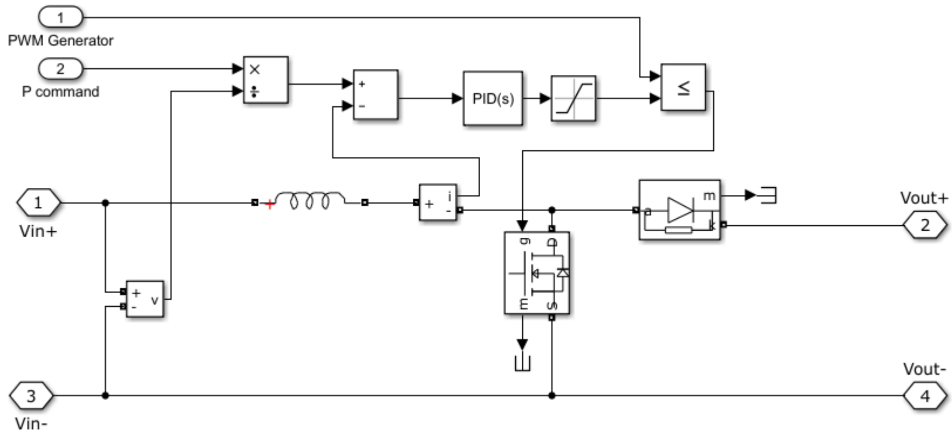


Fig. 1. Simulation model of a hybrid storage system

This model presents an active circuit of a hybrid electric energy storage device consisting of a lithium-ion battery and a unit of supercapacitors having the corresponding characteristics. The temperature effect and the aging effect of the batteries were not taken into account during the simulation. The effect of battery self-discharge was not considered as well. Fig. 2 illustrates a model of DC-DC converters for batteries and supercapacitors, which constitute one of the main components of HESD.

a



b

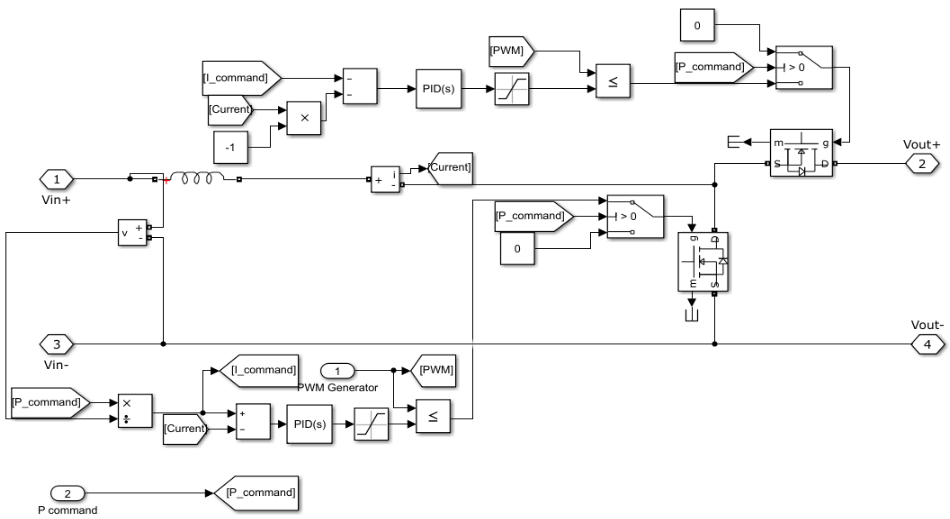


Fig. 2. The boost converter model (a), the buck/boost converter model (b)

As a result of the simulation, the dependences of the generated power by the battery P_{bat} and supercapacitors P_{sc} on time period t were obtained, as shown in Fig. 3.

Having analyzed these dependencies, it is worth noting that there are some differences in the pattern of power output to the network. Since the specific feature of SC is the quick discharge of the unit with the output of a large amount of power to the network, it is expedient to use this storage device to compensate for peak dips. Slow discharging, with gradual delivering power to the network, is typical for batteries, which will allow compensation for longer power dips. Also worth noting is the increase in the lifespan of batteries due to reducing the influence of peak loads when used together with supercapacitors.

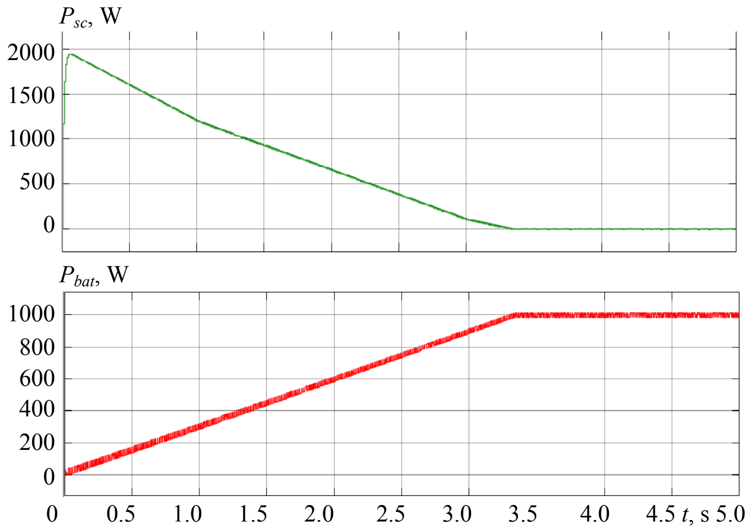


Fig. 3. The diagram of generated power by the battery and supercapacitors

Fig. 4 illustrates a diagram of output power P_{out} by a hybrid electric energy storage device to the grid compared to the required power P_{req}, combining the advantages of two types of energy storage devices.

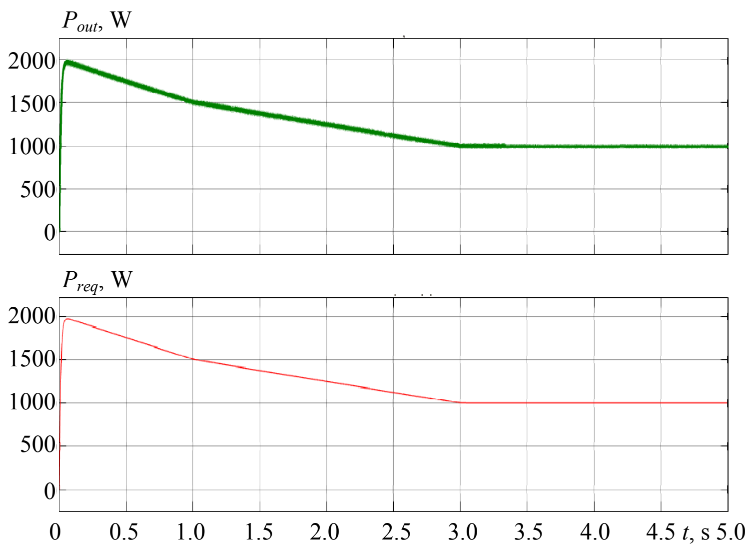


Fig. 4. The diagram of power output by a hybrid electric energy storage device to the grid

Based on the results obtained, it can be concluded that the use of hybrid electric energy storage devices will allow one to efficiently solve the tasks associated with leveling the load curve. Since most load curves of industrial enterprises are characterized by a sharply fluctuating pattern, the use of supercapacitors together with batteries will allow one to more efficiently "utilize" excesses and implement power "dips" leveling. Hybrid storage devices, compared to storage devices, comprising only batteries, have the following advantages:

– an increase in the electric energy storage device peak power;

– an increase in the electric energy storage device operation time due to a decrease in the impact of peak load on the battery;

– reduction in power reverse time, since supercapacitors are characterized by quick response.

However, it is worth noting that the electric power transfer from the storage device to the load is subject to compliance with the quality parameters of electric power, and this requires achieving electromagnetic compatibility of objects with their cost efficiency accounted for [20].

Power increase ratio in the hybrid energy storage system

As it was mentioned previously, the use of the battery together with SC allows one to increase the total capacity of the electric energy storage device. Let us compare the capacity of a hybrid storage device with a storage device comprising only batteries.

The maximum current in the battery is reached at the end of the load pulsed current. However, the maximum battery current at the $n^{-\text{th}}$ pulse depends on the initial conditions. Provided that $n \to \infty$, the maximum battery current is determined by the following equation:

$$I_{b,\max} = I_0 \left(1 - \frac{R_b}{R_{SC} + R_b} \frac{e^{-\beta DT} \left(1 - e^{-\beta(1-D)T} \right)}{1 - e^{-\beta T}} \right) = I_0 (1 - \zeta_\chi) = \frac{1}{\gamma},$$

$$\beta = \frac{1}{\left(R_b + R_{SC} \right) C_{SC}},$$

where I_0 – current of the load; R_b – internal battery impedance; R_{SC} – active resistance of the SC; C_{SC} – capacity of the SC; D – fill factor of the pulsed load current; T – period of the pulsed current; ζ_c – distribution ratio.

The distribution ratio can be determined by the equation

$$\zeta_c = \frac{R_b}{R_{SC} + R_b} \frac{e^{-\beta DT} \left(1 - e^{-\beta(1-D)T} \right)}{1 - e^{-\beta T}},$$

where γ – power increase ratio of HESD, which equal to:

$$\gamma = \frac{1}{1-\zeta_c} = \frac{1}{1 - \dfrac{R_b}{R_{SC}+R_b}\dfrac{e^{-\beta DT}\left(1-e^{-\beta(1-D)T}\right)}{1-e^{-\beta T}}}.$$

Provided that there are no supercapacitors the distribution ratio is equal to zero, $\zeta_c = 0$, while the power increase ratio is equal to unit $\gamma = 1$ and $I_{b,\max} = I_0$. This means that the load is supplied by the battery. A hybrid energy system is capable to supply a more powerful load than a single battery. If the battery rated current is I_b, then according to the expression $i_b(t) = \frac{1}{R_b}\left[U_b - U_0(t)\right]$ the new possible load current for the hybrid energy system can be determined according to the equation:

$$I_0 = \gamma I_b,$$

and the maximum (peak) power

$$P_{\max} = I_0 U_b = \gamma I_b U_b = \gamma P_l.$$

In the presence of SC, the power increase ratio γ makes more than 1. This ratio shows the amount of extra power that a hybrid energy system can accumulate compared to a single battery. It is also worth noting that the power increase ratio γ depends on the frequency f and the fill factor D of the load pulsed current. Fig. 5 illustrates the dependence of the power increase ratio γ on the frequency and the fill factor D of the pulsed current.

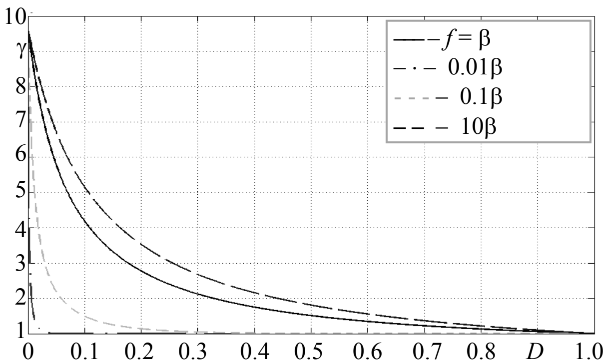


Fig. 5. The dependence of the power increase ratio γ on the frequency and the fill factor D

It is seen from the diagram that the less the frequency of the pulsed load current (approaching the direct current), the smaller the power increase ratio γ for all values of the fill factor D. The more the frequency of the pulsed load current approaches the internal frequency of the system, the less the increase in the power increase ratio γ, the limit of which is reached at $f = 10 f_{syst}$. For any frequency, the power increase ratio γ reaches its maximum at $D \to 0$. In this case: $\lim_{D\to 0} \gamma = \frac{R_{SC} + R_b}{R_b} = 9.6$. It means that by theory the maximum possible value of output power of the hybrid energy storage system is 9.6 times larger than a single battery having the same parameters. When applying the same type of the load, an increase in the electric capacitance of SC gives an increase in ζ_c and γ, due to large distribution of current on SC. It is also evident that the lower the internal resistance of SC, the better the characteristics of the hybrid energy storage system.

CONCLUSION

The issue of the combined use of supercapacitors and batteries, considered in the paper, allows one to conclude that the use of such hybrid energy storage devices can contribute to efficient solving the task of leveling the load profile, resulting to an increase in the total capacity and operation time of the storage device. It is worth noting that leveling the load profile gives the most important effect in terms of the energy grid and is economically stimulated. It renders possible to increase the installed capacity utilization factor for power stations, while reducing the idle time of generating capacities and reducing specific fuel consumption.

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