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# Investigation of Smart Grid Operation Modes with Electrical Energy Storage System

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**Abstract:** The paper considers the issues of maintaining an equality of flow in generated and consumed electric energy in an electric network incorporating an electric power storage system. An analysis of ways to equalize the energy and power balance was carried out, and the advantages of using electricity storage systems in electrical networks was assessed. Upon simulation using the Power Factory program, we noted that, after switching on the load, a transient process occurs, characterized by a jump in active power, which was caused by the need for time to initiate the electric energy storage system. However, immediately after this, the process of issuing the accumulated energy to the electrical network and compensating for energy consumption began. Moreover, when the load was disconnected, there is a certain dip in the active power curve and a further increase in consumption. This was found to be due to the transition of the electricity storage system to the modes of energy storage and battery charging. As a result of this simulation, data on the charging and discharging time of the electricity storage system were obtained. The studies show that the use of electricity storage systems in electrical networks allows for the stable operation of all main generators, and thus increases the safety and reliability of the entire system.

**Keywords:** electricity storage system; distribution network; power balance; Smart Grid; modeling of network modes

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## 1. Introduction

One of the urgent problems facing the energy industry in the context of ensuring security of supply and operational security, is a significant increase in the maneuverability of the power system, which, while previously insufficient, has become acute in the context of the rapid expansion of capacities from renewable energy sources [1–3].

At present, many technologies can be used to solve this problem, such as highly maneuverable thermal generation with the possibility of a quick start-up, highly maneuverable hydro-storage power plants, electric energy storage systems for maintaining and regulating frequency, consumer-regulators based on thermal energy storage technologies, and electric energy storage systems based on battery [4–6].

In the current literature, storage methods are being investigated for both microgrids and large consumers of electrical energy [7,8]. One way of storing energy is power-to-gas technology. The essence of this technology is that excess electricity is used to produce hydrogen via the electrolysis process. This hydrogen is subsequently converted to methane by exposure to a carbon source. The gas must be stored in special tanks and is then consumed as needed. Power-to-gas technology is most efficient means of long-term energy storage. With daily charging and discharging, the energy loss is very significant.

Pumped storage power plants are a time-tested technology and widely employed to cover imbalances in electrical networks. The main advantage of a pumped storage power plant is its high efficiency, but its expensive and lengthy construction and maintenance incur significant costs [9,10].

Gravitational energy storage systems, the principle of operation of which includes gravity and friction, are very inefficient; therefore, they are not widely used [11].

At present, the independent application of electricity storage systems (ESS) as an additional "active" element of distribution electric networks [12,13] has not been sufficiently studied. The use of ESS provides new opportunities for managing the electrical network, namely, smoothing load peaks and voltage regulation [14–16].

An efficient distribution electric network requires the application of intelligent methods of managing distributed energy sources or loads and the use of automated multi-functional devices that change the configuration and/or parameters of the network by generating the necessary control influences in each specific situation [4,17,18]. This sort of network is called a Smart Grid [5,19,20]. An ESS is considered a multifunctional device, and includes the following components [21,22]: a semiconductor converter that can work in the rectification mode (when the battery is being charged) or in the inverting mode, converting a constant voltage from AB alternating voltage 50 Hz; a long-term (electrochemical) storage system (otherwise known as a battery); and an automated control system, the functionality of which depends on the tasks to be solved. The choice of ESS is mainly based on the determination of two parameters: power and storage capacity [6,23]. To select these parameters, it is advisable to use the actual daily load schedules.

The incorporation of an ESS into a grid provides a complete solution to a significant number of known problems that currently exist in distribution networks. The following ESS functions are of the greatest interest [24,25]:

- Power flow management: changing the direction of power flow, reducing electricity losses, smoothing peak consumption;
- Voltage regulation: stabilization of voltage levels at the end of a heavily loaded feeder, maintenance of the specified power factor, elimination of restrictions on the operating modes of the distributed generation system, elimination of the need to perform operations with voltage regulation transformer devices, provision of specified limits for some indicators of electricity quality.

The purpose of the article is to analyze the balance and flows of generated and consumed electrical energy in the electrical network, incorporating an ESS and modeling their operational modes.

## 2. Research Method

### *2.1. Equalization of Flows of Generated and Consumed Electrical Energy*

The operation of any electric power system involves the simultaneous production and consumption of electricity. Hence, equal-power oscillations must be generated by the sources feeding the network and the power consumed by energy consumers. Violations of this equality lead to a change in the parameters of the network in terms of voltage and frequency and, in case of an increased deviation, to a loss of dynamic stability and a violation of the normal functioning of the system.

An example of changing the required power consumption of the network is shown in Figure 1.

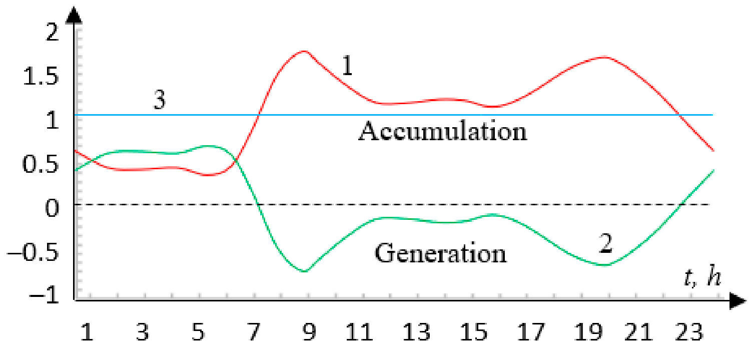


**Figure 1.** Dependence graphs for normalized capacities: **1**—graph of the electricity consumption function *Pp.nor(t)*; **2**—graph of the function for ESS *Pp.nor(t)*; **3**—the graph of the function of the sum of the powers of all generators *Pg.nor(t)* = 1.

In the figure, the abscissa axis represents time (in hours), and the ordinate axis represents the value of the required power consumption normalized relative to some average value. The uneven character of electricity consumption between its peak and minimum values has an extremely unfavorable effect on the dynamic stability and other performance indicators of the power system.

There are two possible ways of maintaining a continuous equality of generated and consumed electricity over time. The first method consists of the constant monitoring of the consumption power and the corresponding regulation of the power of the electricity sources (until they are turned off), so that the equality between the two indicated powers is continuously maintained. The second method consists of including an ESS that stores electricity when its consumption is reduced and, after conversion, feeds the electrical network when a certain level of consumption is exceeded in the electrical network.

Let us compare the methods in use at present. Hydro-accumulating power plants help to balance the load schedule of the power system through release and pumping, but the process of pumping water from the bottom up and back inevitably involves losses; thus, the coefficient of efficiency of the PSH is about 75%. In addition, the frequent adjustment of the power of almost any type of electric generators has an extremely adverse effect on their operation. Disadvantages also include the high cost and long period of construction of the PSH. This is a serious drawback in maintaining the balance between generated and consumed electricity.

In hydrogen power plants, chemical energy is directly converted into electrical energy (the reverse electrolysis process)—accordingly, the need for turbines is eliminated, and the conversion efficiency reaches 50–65% (coefficient of efficiency at the level of the best natural gas thermal power plants). The stations are ecologically clean (unlike gas turbines, which pollute the atmosphere with nitrogen oxides even when burning 100% hydrogen), are silent, and produce thermal energy. The technology, however, comes with disadvantages. These include the fact that hydrogen is extremely flammable and explosive. Moreover, hydrogen fuel cells are quite expensive to operate, mostly due to the cost of the processes associated with the release of free hydrogen from its natural forms.

With the battery ESS method of equalizing the flows of generated and consumed energy, electrical energy supply is stable, and an almost constant operation of all generators included in the system is assumed. This positively affects its reliability, durability and safety. At the same time, regulation of the operating mode in case of variable current needs in the power system in terms of consumed power is carried out only at the expense of the ESS battery. The battery ESSs themselves work in one of three modes: accumulation of electricity, its storage and transformation with the transfer of the received electricity (electric current with a frequency of 50 Hz) to the general network.

Each of the considered methods has its own advantages and disadvantages. Therefore, the applicability of each method must be considered for specific conditions. If there are large water supplies that can be pumped, then the first method is preferred. In the absence of water supplies, as a rule, the technology described in the other methods is used.

However, at present, the battery ESS method is increasingly preferred, since competitive storage devices with high charging and discharging currents are constantly being developed based on the existing backlog in the field of converter technology and supercapacitors. The development of drives with large cycling resources is also underway.

### 2.2. Energy and Power Balance Equation in an Electrical System with ESS

For such a system, the energy balance equation for a relatively short period of time $\Delta t$ for any value of time $t$ will have the form:

$$W_g(\Delta t, t) = W_{con}(\Delta t, t) + W_{ESS}(\Delta t, t), \quad (1)$$

where

$W_g(\Delta t, t)$—electric energy supplied to the network by all generators feeding it during time $\Delta t$;

$W_{con}(\Delta t, t)$—total energy consumed by all consumers connected to the network;

$W_{ESS}(\Delta t, t)$—energy associated with ESS connected to the network.

ESSs have three modes of operation: energy storage $W_{ESS}(\Delta t, t) > 0$, its storage at $W_{ESS}(\Delta t, t) = const$ and generation at $W_{ESS}(\Delta t, t) < 0$ with the supply of an alternating current with an industrial frequency of 50 Hz to the network.

For the electric power system, an expanded form of Equation (1) in the mode of accumulation of excess energy produced has the following form:

$$\sum_{i=1}^{K} \int_{t_1}^{t_2} P_{gi}(t)dt = \sum_{i=1}^{M} \int_{t_1}^{t_2} P_{coni}(t)dt + \sum_{i=1}^{T} \int_{t_1}^{t_2} P_{ESSi}(t)dt, \quad (2)$$

where

$P_{gi}$—the power of the $i$-th generator;

$K$—the number of such generators;

$P_{coni}$—the power consumed by the $i$-th load;

$M$—the number of such loads;

$P_{ESSi}$—power of the $i$-th ESS;

$N$—the number of such ESSs.

The same equation in the mode of returning the stored energy to the network:

$$\sum_{i=1}^{K} \int_{t_1}^{t_2} P_{gi}(t)dt = \sum_{i=1}^{M} \int_{t_1}^{t_2} P_{coni}(t)dt - \sum_{i=1}^{T} \int_{t_1}^{t_2} P_{gESSi}(t)dt, \quad (3)$$

where $P_{gESSi}$—the power generated by the $i$-th ESS.

We will take the integration interval $\Delta t$ = $t_2$—$t_1$ to be quite small, considering that, during the time $\Delta t$, the total power of all consumers changes relatively smoothly and cannot suddenly jump to a relatively large value. Therefore, we can take $\Delta t$ = 1 min.

We denote the total power of all generators that determine the left side of Equation (2) as $P_{g.sum}$, its average value for 24 h as $P_{av}$, and the normalized value as $P_{g.nor} = P_{g.sum}/P_{av}$. In an ideal case, the power of all generators for the entire operation time should remain unchanged, hence, $P_{g.sum}$ = const; therefore, the normalized value of $P_{g.nor}$ = 1 = const. Guided by the same rule, we denote the normalized power value consumed by all loads as $P_{con.nor}$, and the normalized power value of all ESSs as $P_{ESS.nor}$. Considering the entered notations, the equation of the balance of the normalized power values for the ideal case of operation of the electric power system at any moment of time $t$ will take the form:

$$P_{ESS.nor}(t) = 1 - P_{con.nor}(t). \quad (4)$$

An example of graphs of functions corresponding to Equation (4) is shown in Figure 1, where 1 is the graph of the electricity consumption function $P_{con.nor}(t)$; 2—the graph of the function for the ESS of electricity $P_{con.nor}(t)$, 3—the graph of the function of the sum of the capacities of all generators $P_{g.nor}(t) = 1$. When $P_{ESS.nor} > 1$, the ESSs operate in the electricity storage mode; when $P_{ESS.nor} < 1$ its generation and return to the network.

### *2.3. Structural Diagram of a Smart Grid with ESS*

The following principles will provide the basis for the construction of a power plant incorporating an ESS:

- Summarizing the capacities of a large number of generators of the same type (in this case, it is advisable to take a generator with a frequency of 50 Hz and a capacity of at least 200 kW as a basis);
- Each such generator is powered by a separate power source;
- Total energy from generators is supplied to the general network through transformers;
- Electronic systems of automatic adjustment are used to stabilize the generated oscillation parameters;
- Control of the power plant is remote, by radio channel or fiber-optic line.

The Smart Grid scheme, which realizes the implementation of the formulated principles of construction of ESS is shown in Figure 2.

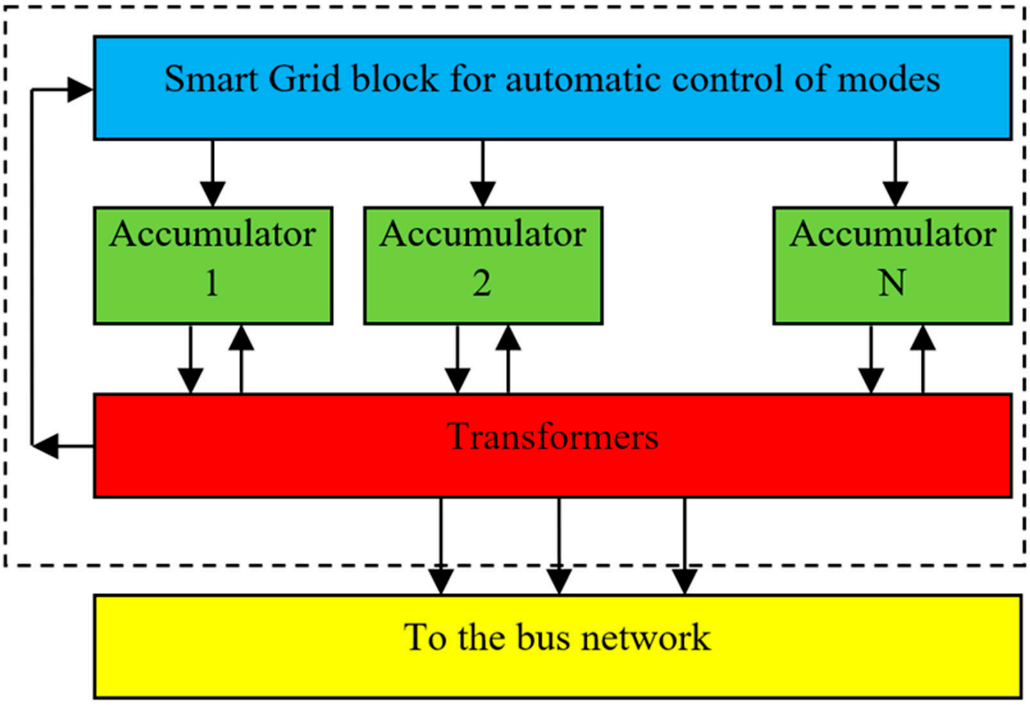


**Figure 2.** Structural diagram of Smart Grid with electricity storage system.

The scheme contains $N$ identical ESSs (Figure 2), a group of high-voltage transformers for connecting generators to the general network, a Smart Grid control system and parameter stabilization of all semiconductor generators.

At the time of ESS connection to the general power supply system, it is necessary to obtain the parameters of the output voltage (amplitude, frequency and phase) that correspond to the similar parameters on the power grid buses. This task is performed by the automatic regulation system, the central link of which is the Smart Grid block (Figure 2).

The power plant is controlled remotely via a radio channel or a fiber optic line. With the help of such a control system, the power plant can switch from electricity storage to generation mode any number of times a day in a few seconds. With the help of the same control system, all parameters of the power plant are continuously monitored, and in case of abnormal situations, the necessary decisions are made.

*2.4. Algorithm for Managing Electricity Storage Systems*

The maximum total power generated after ESS conversion and supply to the network is:

$$P_{ESS} = P_{con.\ peak} + P_{gen}, \quad (5)$$

where $P_{con.peak}$—the peak value of power consumption;

$P_{gen}$ = const—total power, which is continuously generated by all power plants included in the system.

Let us consider how the process of accumulating electricity and introducing it into the power system can be operationally managed to maintain a continuous balance between the total power generated and the power consumption according to (2) and (3). Let us assume that the output power of the ESS is determined by the expression:

$$P_{ESS.1} = (P_{con.peak} + P_{gen})/M, \quad (6)$$

where $M$—the total quantity of equal power EES.

For smoother power regulation, it is advisable to take $M > 10 \div 20$. If the total power consumption is $P_{con} < P_{gen}$, it is necessary to accumulate electricity, if $P_{con} > P_{gen}$ after its conversion, it must be introduced into the power system. Let us consider two algorithms of such a process of energy accumulation and its consumption: continuous and predictable.

In the continuous mode, the voltage on the busbars of the power plant $U_{bus}$ is compared with the required nominal value $U_{nom}$ and, depending on the difference between their values (the error signal $\Delta U = U_{bus}—U_{nom}$, as well as the sign of the derivative $d\Delta U/dt$), a decision is made to enter $K_1$ ESS into storage mode or $K_2$ generation mode oscillations with a frequency of 50 Hz. This operation is performed automatically by means of a microprocessor-based automatic control system.

With the predicted control mode, a known graph of the dependence of the power consumption on the time Pcon(t) is assumed during the day and every day. As a result, it is possible to predict with a high degree of probability the law of change of the total power of the ESS for each day of the week:

$$P_{ESS}(t) = P_{gen} - P_{con}(t). \quad (7)$$

Since it is almost impossible to accurately observe this law, the actual dependence of $P_{ESS.act}(t)$ from the required will differ by an amount that should be as minimal as possible; hence:

$$\Delta P(t) = P_{ESS.act}(t) - P_{ESS}(t). \quad (8)$$

At the same time, the energy consumed or spent by the ESS will be recorded in the form of an objective function, which should also be as minimal as possible; thus:

$$H = \min\Psi\left[\int_{t_1}^{t_2} |\Delta P(t)| dt\right]. \quad (9)$$

This procedure of minimization of Equation (9) should be considered as a typical problem of variational calculus related to the minimization of the integral that characterizes the research process. At the same time, two criteria for such minimization are possible: (1) minimax, in which the maximum discrepancy between the actually obtained and required dependencies is minimized, and (2) the criterion for the minimum of the sum of the squared deviations, which, in this case, will take the form:

$$H = \min \sum_{i=0}^{N} \Psi \left[ \int_{t_1}^{t_2} |P_{ESS.act}(t_i) - P_{ESS}(t_i)| dt \right]^2. \tag{10}$$

where $N$—the number of measurements of the generated electricity and other indicators that determine the quality of the electrical system.

The discrete character of the function should be taken into account in relation to the number of ESSs that are put into operation:

$$P_{ESS.act}(t_i) = P_{ESS0} K_1 \text{ or } P_{ESS}(t_i) = P_{ESS1} K_2. \tag{11}$$

where $K_1$ is the number of ESSs included in operation at each of the time points $t_i$ in the electricity storage mode when $P_{con} < P_{gen}$;

$K_2$—the number of ESSs included in operation at each moment of time ti in the generation mode when $P_{con} > P_{gen}$.

The numbers $K_1$ and $K_2$ are determined according to the algorithm based on the minimization of the objective Equation (10). The easiest way in this case is to sort through a certain number of options. When determining the optimal option, the exponential nature of the process of accumulation and discharge of ESS should also be taken into account. Thus, the ultimate goal of preparing the action program for the next day of operation of the electric power system is to calculate the dependence functions $K_1 = \Psi_1(t)$ and $K_2 = \Psi_2(t)$.

## 3. Results and Discussions

Let us consider an example of the operation of an electrical network with a battery ESS and perform a simulation of its operation modes in the Power Factory program.

Figure 3 shows the test electrical network for testing ESS. The test network model was implemented using DIgSILENT Power Factory software, which allows for the simulation of the processes in the electrical network, as well as calculation of the power flows in the lines, currents, time of charge and discharge of ESS, etc.

The network consisted of a generator G3, a transformer T3 and three outgoing lines that feed the loads Load 1, Load 2 and Load Step. The network also contained an ESS consisting of a battery and a converter. This system was connected to the network through matching transformer T4.

The battery has the following parameters:

| | |
|---|---|
| Capacity of one element, A·h. | 30 |
| The minimum voltage of the empty element, V | 12 |
| The minimum voltage of the empty element, V | 13.85 |
| Number of elements connected in parallel, pcs. | 60 |
| Number of consecutive links, pcs. | 65 |
| Nominal voltage of the source, kV | 0.9 |
| Internal resistance of the element, Ohm | 0.001 |

Figure 4 shows the model of the ESS charge–discharge regulator used in these calculations. This model takes into account the algorithm of interaction of real ESS with the network, and also considers the limitations inherent in real ESS.

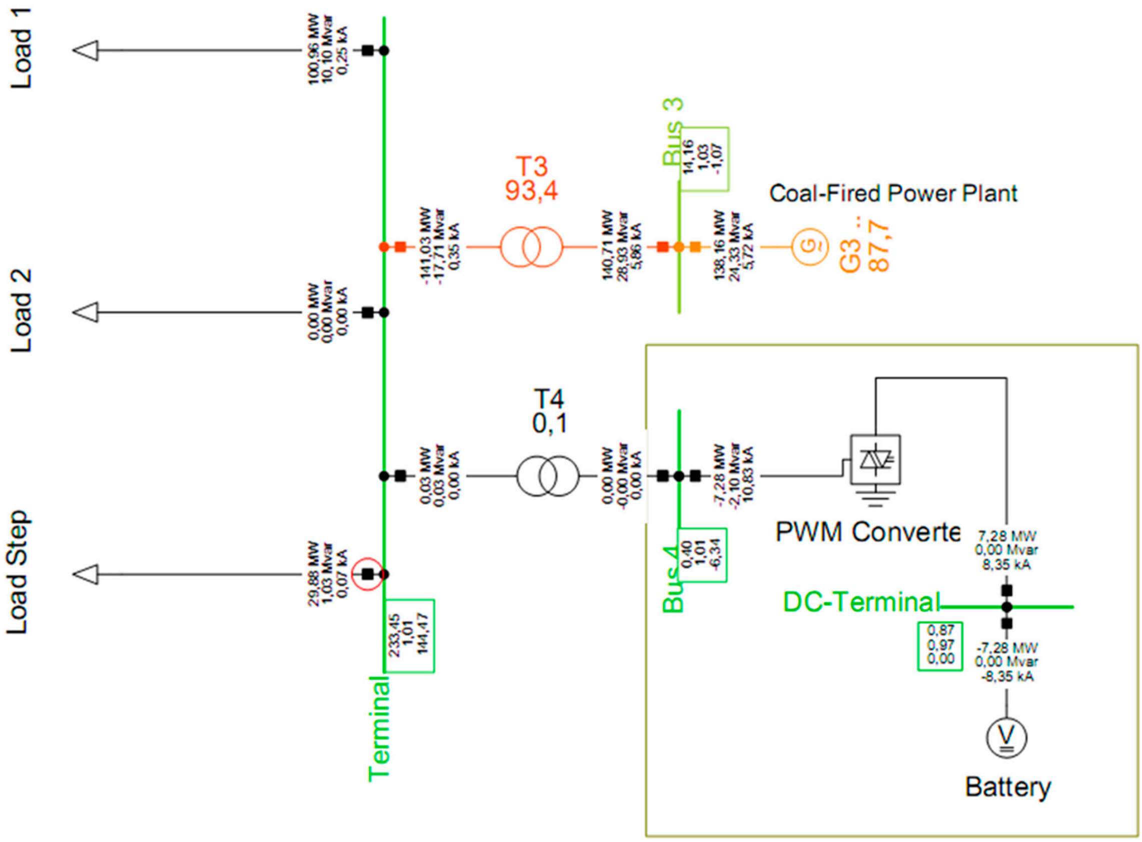


**Figure 3.** Test network for testing ESS.

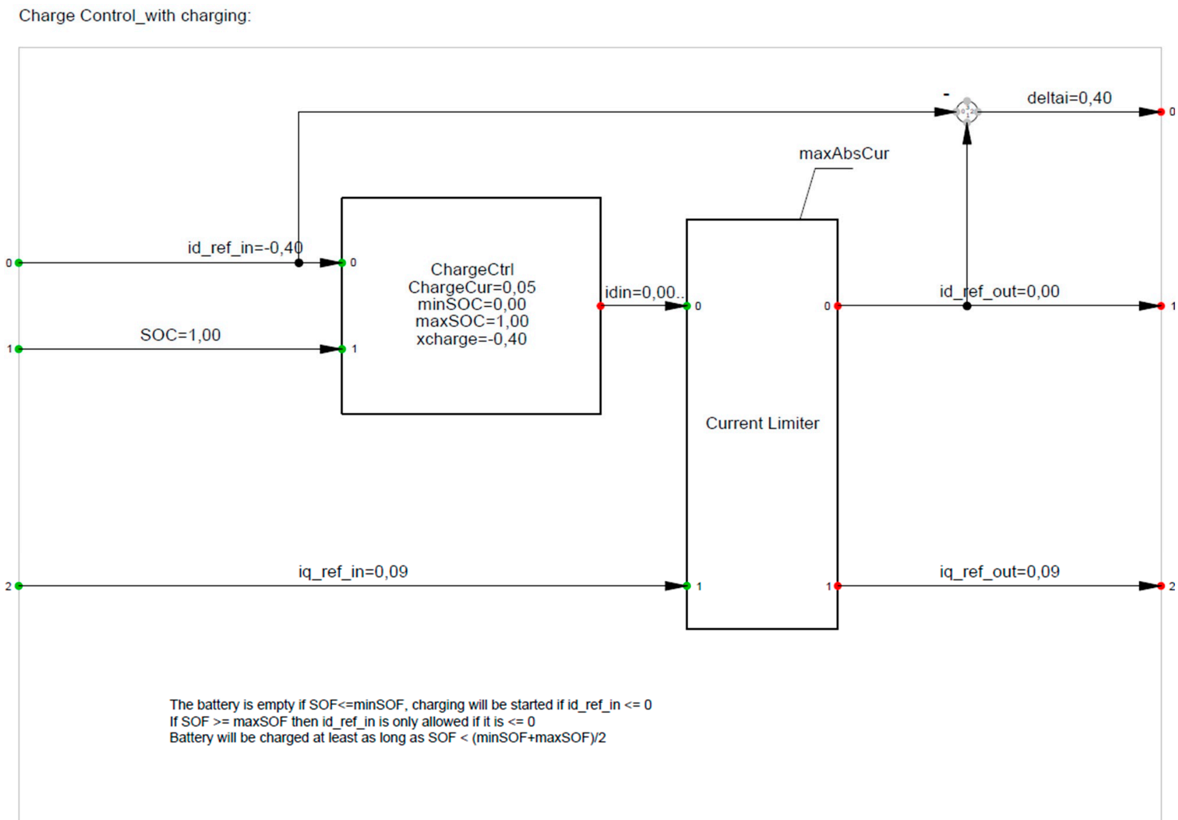


**Figure 4.** Model of charge–discharge regulator.

Figure 5 shows the result of the simulation.

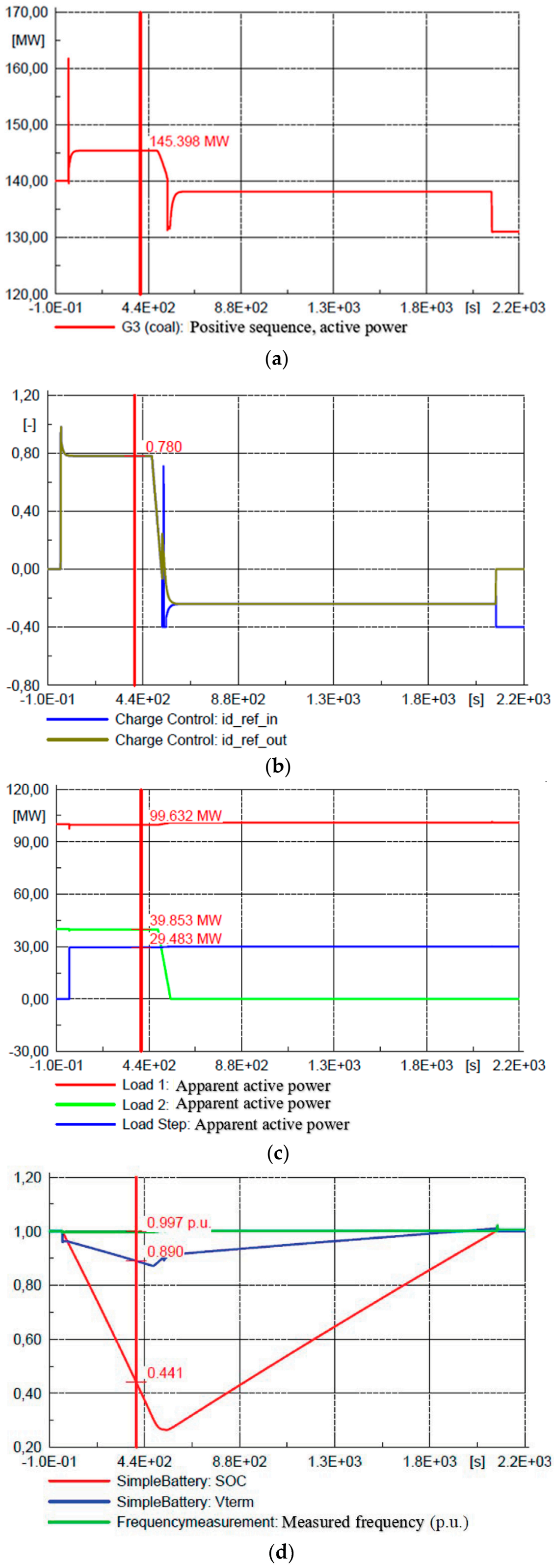


**Figure 5.** The results of test studies of the SNE when the network load changes. (**a**) Active load schedule of generator G3, taking into account the influence of the ESS. (**b**) ESS battery charge charts. (**c**) Timing diagram for load initation and end in the network. (**d**) Change in the capacity and voltage of the ESS batteries over time.

In order to cover as many options as possible and see the influence of ESS on the most general case, we simulated a network with the most typical parameters and generation and load power values. At the same time, the average total load power was about 140 MW and the power of the ESS inverter was 30 MW, which is comparable to the magnitude of load surges. This value was about 20% of the total load and is the most typical for such electrical networks.

During the experiment, Load 1 was about 100 MW and did not change throughout the experiment, Load Step was about 30 MW and started at a certain initial time, while Load 2 load was about 40 MW and ended some time (about 10 min) after the Load Step load is initiated.Iin this way, the mode of changing the load in the network was implemented. This process is reflected in the time diagram for engaging and disengaging the load in the network (Figure 5c).

After the Load Step load begins, a transient process occurs in the network, characterized by a certain jump in active power (Figure 5a), associated with the time requirement for loading the battery ESS. Immediately after initiating the SNE, the issuance of the accumulated energy to the network begins, and the compensation of energy consumption occurs. In this case, the total load increased by only 5 MW, and not by the Load Step value of 30 MW (Figure 5a). Figure 5D illustrates the process of discharging the batteries and their residual capacity (descending section of the Simple–Battery: SOC curve), as well as the voltage on the batteries (curve SimpleBattery: Vterm).

When Load 2 was disconnected, at the next stage of modeling, there was first a certain dip in the active power graph (Figure 5a) and a further increase in consumption, which is due to the transition of the SES to the energy storage and battery charging mode (growing segment of the SOC graph, Figure 5d). The SOC units are percentage points (0% = discharged SOE; 100% = charged SOE).

Figure 5b shows the discharge and charge currents of the SNE batteries in relative units during the experiment.

After the end of the SNE battery charging process, the active power of the network decreased to 130 MW (Figure 5a), the battery capacity was 1.0 relative units (Figure 5d), and the charging current of the batteries decreased to zero (Figure 5b).

The results of calculating the steady state of the test network, particularly the active power flow at the end of the experiment, are shown in Figure 3. At the end of the load experiment, Load 2 ended and the SES batteries were fully charged; the power of these elements was 0 MW.

Thus, the interaction between the ESS and the network can be characterized as the connection of an additional load to the network when there is an excess of power or a decrease in consumption: the ESS charge mode. Accordingly, the return of power to the network during the period of increased consumption was the mode of discharge of the ESS and the issuance of stored energy.

According to the calculation results, the ESS discharge process takes place from 60 s to 543 s and reaches 0.264 (Figure 6). Here, SOC units are seen as percentage points (0% = discharged ESS; 100% = charged ESS).

The total simulation time was about 43 min. The full charge of the ESS was observed in the interval from 543 s to 2048 s. The inverter was connected to the 0.4 kV busbar system and had a current of 33.8 kA at the ESS discharge. Next, an ESS charge with a current of 10.83 kA was observed. The converter used in the simulation had a capacity of 30 MVA. The operational limits of the voltage regulation were set to ±30 MVAR.

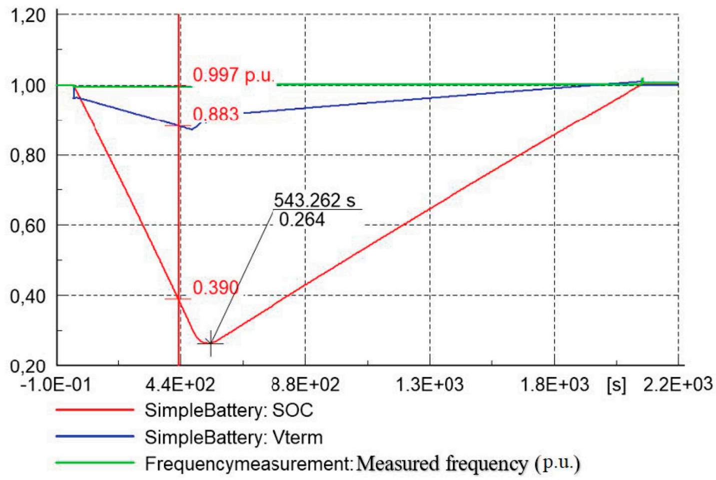


**Figure 6.** Results of simulation of discharge and charge of ESS.

## 4. Conclusions

The comparative analysis of two methods of maintaining the equality of the generated and consumed power of electric flows in the energy system makes it possible to clearly determine the advantage of battery ESS, as these evidently ensure the stable operation of all main generators in the network, and thereby increase the safety and reliability of the entire system.

The considered principles of the construction and management of an electrical system with a battery ESS allow for us to move to the experimental stage of creating and testing the operation of a new type of Smart Grid electrical network.

Compared to the hydroaccumulating ESS, battery ESS significantly reduces capital costs in construction, since neither water basins occupying a large area nor dams are needed. In any case, operating costs will be significantly lower, since battery ESS can be managed remotely, without service personnel. At the same time, the power plant will be more reliable and environmentally friendly and hold a service life of tens of years.

The results of modeling the processes that occur in the electrical network when the magnitude of the electrical load changes show how the presence of a battery ESS affects the alignment of the load curve. The simulation results show that the ESS discharge process lasts up to 543 s and reaches a value of 0.264 of the full capacity. The full charge of the ESS is observed in the interval from 543 s to 2048 s. The inverter has a current of 33.8 kA when the battery ESS is discharged, and then reaches a current value of 10.83 kA. In the simulation, a converter with a capacity of 30 MVA with voltage regulation limits of $\pm$30 MVAr was used.

The obtained results show that in the electric network with a battery ESS, when the load changes from +30 to $-$45 MW from the steady-state value, the uneven load curve of the generator ranged from +5 to $-$2 MW from the steady-state value. Thus, the use of ESS makes it possible to reduce the uneven load curve from +21%/$-$32% to +3.5%/$-$1.4%, which proves the high efficiency of this method.

Further work will be devoted to the practical verification of the obtained results using a physical battery ESS model.

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