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Rational Integration Level of Solar Generation in Traction Power Supply Substations for Supplying Auxiliary Consumers

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Abstract

The paper considers the existing levels of electricity consumption by responsible consumers of gas and evaluates the use of solar generation to meet these needs. Using mathematical modeling based on real statistics, the dependences of solar power on the time of day are determined, which allows to estimate the random component of solar generation and determine the possibility of compensating the variability by using AB. The method of choosing the optimal capacity of the battery, taking into account the stochastic nature of solar generation is presented.

KEY WORDS: *traction power supply facilities, auxiliary needs systems, solar generation, batteries, mathematical modeling*

1. Introduction

The development of humankind is inextricably linked with the increase in the consumption of energy resources [1]. At the same time, there is a negative impact of environmental pollution factors, which leads to an increase in CO levels$_2$ and other harmful components [2]. Recently, many efforts have been made to reduce the harmful effects on the environment by creating various programs to reduce the use of fossil fuels (climate agreement, green hydrogen, etc.). The content of these programs determines on the one hand, the reduction of consumption of various types of energy, and on the other hand, the widespread introduction of renewable energy sources (RES) in different sectors of the economy [3]. One of the critical consumers of electricity is electrified rail transport, which is constantly increasing due to known advantages: significant traffic capacity, speed, relative environmental friendliness and more. A difficult task is to find the components that allow you to achieve this goal [4].

Analysis of literature sources in this area indicates two approaches. The first is to assess the effectiveness of the complete replacement of the concept of building the topology of the power supply system of electrified railways [5, 6], which consists in the intensive use of RES (solar and wind generation), power electronics, and converters (storage systems and supercapacitors). This approach is quite costly and requires significant financial investment in railway infrastructure. The second approach involves the partial modernization of some aspects of the existing railway power supply system [7, 8] with the search for opportunities to expand the use of RES and increase the reliability and efficiency of the electricity supply. According to the authors, this approach is more acceptable for the development of Eastern European railways and needs further study.

2. Main Material

The system of providing electricity to railway consumers has a rather complex and branched structure. The main functional elements are traction substations, sectioning supply points (SSP) and parallel connection points (PCP), etc. To ensure reliable and economical operation of these objects, it is necessary to analyze their schematics (Figs. 1-2), given in [9, 10].

One of the responsible components of these facilities is the operation of the system of auxiliary needs designed to ensure reliable operation of protective, measuring, and switching equipment. The specific electricity consumption for the auxiliary needs of modern substations is about 0.3% per 1 kW/h of converted electricity, which, taking into account the significant volumes of consumption by electric transport, is substantial. Fig. 3 shows the scheme of auxiliary needs.

The auxiliary needs consumers on the traction substation should include electric motors of the cooling system of transformers; heating devices for switches (if necessary), distribution cabinets; electric lighting and space heating. The structure of the system's auxiliary needs of traction power supply facilities has specific features: consumers are divided into responsible and not responsible. Responsible consumers of auxiliary needs include control system devices, relay protection, signaling, automation and telemechanics. Cessation of power supply to these consumers, even for a short period of time, leads to a partial or complete termination of the facility. The auxiliary needs of electricity that don't require high reliability include those elements whose interruption in the power supply does not cause significant changes in the operation of the substation (heating, ventilation, lighting, etc.). Recently, there has been a tendency to reduce the power consumption of the auxiliary needs system through the use of more energy-saving equipment (LED lamps, microprocessor relays, modern high-voltage breakers, etc.).

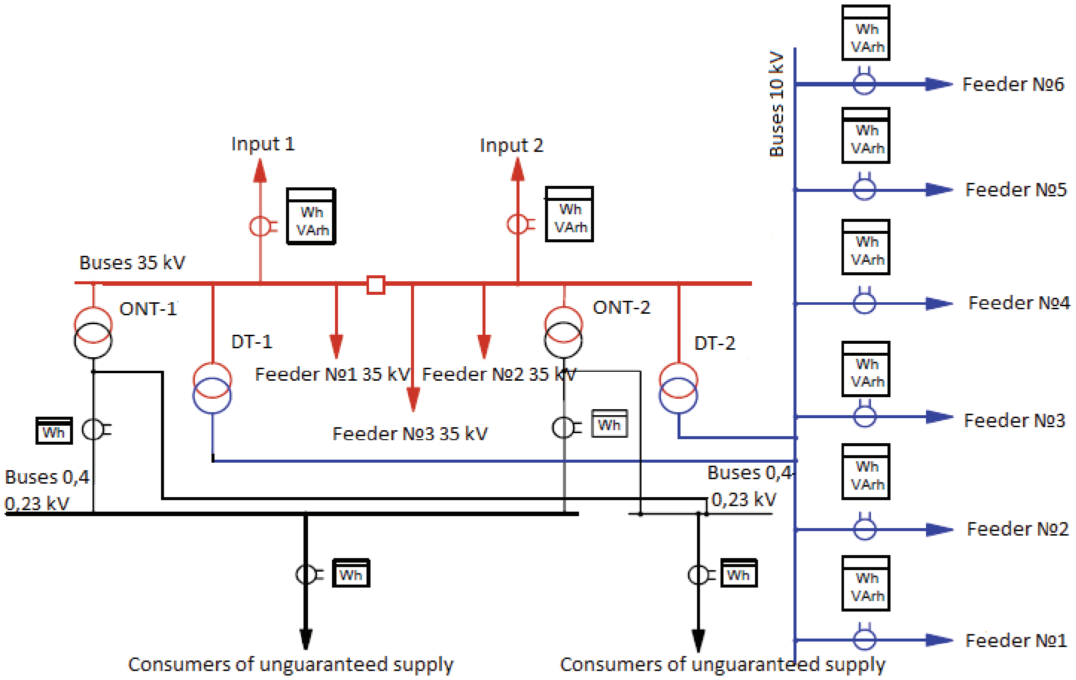

Fig. 1 Simplified schematic diagram of AC substation AC

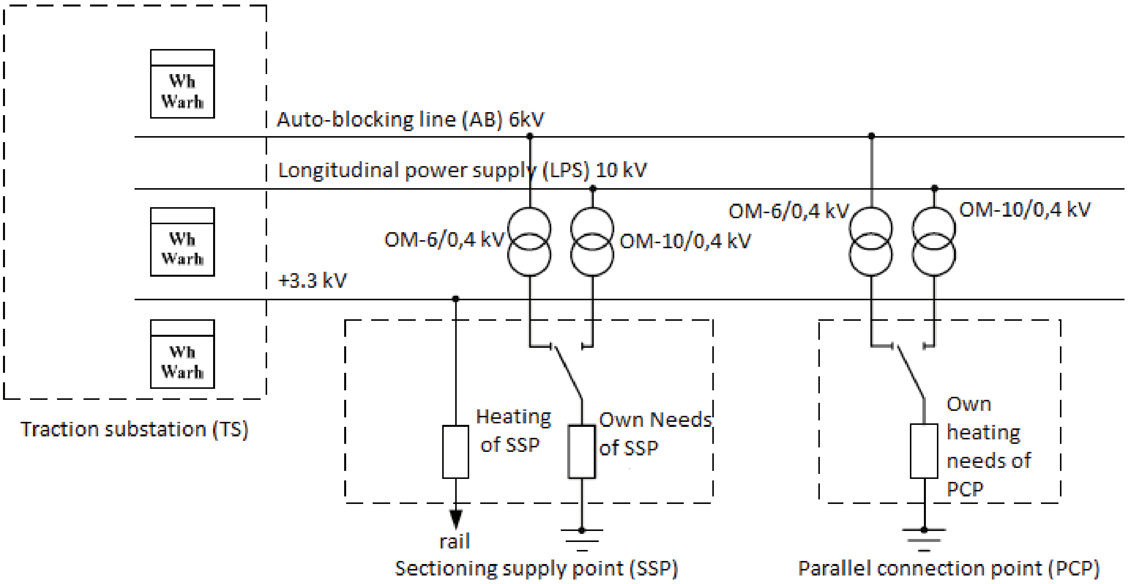

Fig. 2 Schematic diagram of power supply SSP and PCP in the DC system

The power supply of responsible consumers is provided through the bus of guaranteed power supply, others - through the bus of non-guaranteed power supply. To increase the reliability of the power supply system of responsible consumers use batteries (often lead-acid). The peculiarity of their work is the danger of deep discharge, so to control the degree of their discharge using charging and recharging devices (CRD), which perform the function of an energy source and only in the case of complete power failure, are connected to the battery. Due to the noted feature of lead-acid batteries and the inadmissibility of discharging them to 30% of the nominal capacity, there is a need to almost triple the installed capacity to ensure the established requirements for the reliability of the power supply. During operation, the battery must be periodically discharged (to maintain performance), as well as to carry out constant inspection and control of operating parameters. These shortcomings make batteries the most valuable element in the auxiliary needs power supply system.

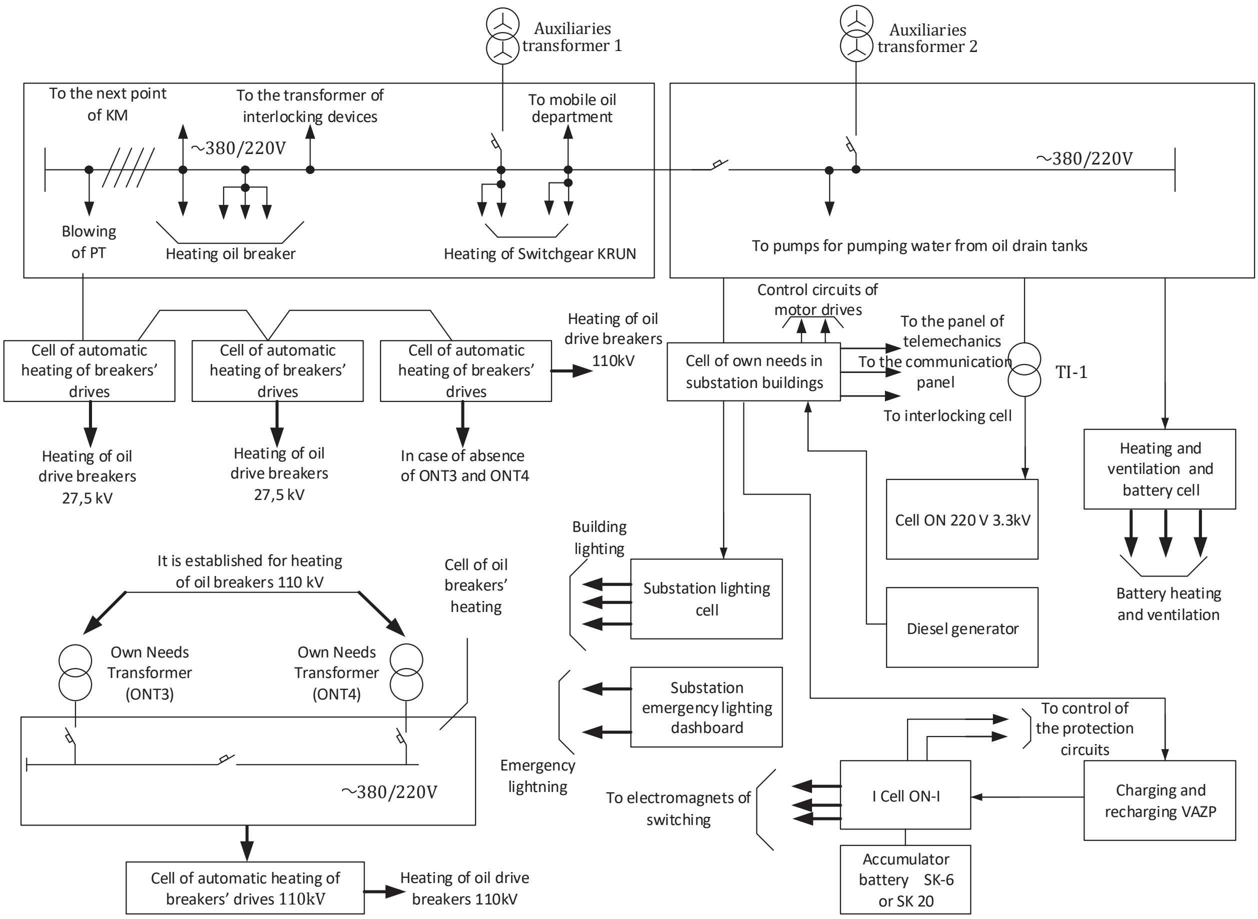

Fig. 3 Generalized scheme of auxiliary needs for the AC substation

Modern lithium-ion batteries do not have these disadvantages, provide a longer service life, allow you to automate the process of diagnosing and controlling the charge, so they are perfect as a source of energy [11-14]. This type of battery also works effectively from distributed generation sources (primarily solar), which allows you to build a compact backup power supply system without the constant operation of the CRD. Such a system is generally called a solar photovoltaic system or solar station (Fig. 4).

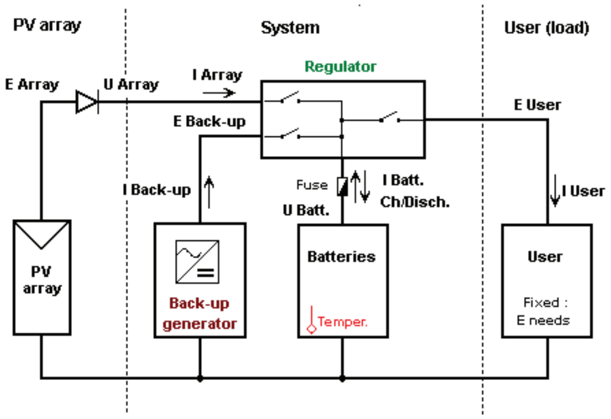

Fig. 4 Functional diagram of the backup power supply system

The following elements can be distinguished in its structure: photovoltaic modules (PV-generator) with supporting armature, communication cables, and, depending on the type of system, electronic inverter and charge controller with battery. In sunny weather, the source of electricity is a solar battery that charges the battery, when it reaches full charge, the solar generator interrupts. Due to the use of the inverter, the possibility of electricity supply to the consumers of auxiliary needs is provided. The charge controller monitors and controls the entire system, primarily to ensure maximum efficiency in the use of generated energy. Some manufacturers include a controlled recharge in the regulator's feature set to equalize the voltage on the batteries. To obtain the required power and operating voltage, the modules are connected in series or in parallel, the more carefully selected modules in the battery (or the smaller the difference in the characteristics of the modules), the less electricity loss.

Photovoltaic modules must be equipped with special protection against excessive discharge, which is provided by disconnecting the load. This protection is activated when the battery voltage drops below the trip voltage. The load cannot be connected until the voltage rises to a certain threshold (voltage connection). Given the above circumstance, when designing power supply system's auxiliary needs for traction power supply elements, it is necessary to determine the optimal capacity of the batteries system, taking into account the possibilities of solar generation in the region (Battery Energy Storage Systems - BESS).

To generalize the problem, it is necessary to create a mathematical model of appropriate adequacy, in which the parameters of the system would be formalized and allow a wide range of options for choosing the most optimal options for the formation of a mathematical model of capacity balancing, i.e. comparison for a long (at least a year) period of time. As the elementary time it is convenient to use 10-minute intervals that allow to observe behavior of system; the availability of this data is also an important factor.

For the considered system, the equation of power balance will look like [15]:

$$V(t)=P_S(t)\pm P_A(t)+P_G(t)-P_U(t), \tag{1}$$

where $P_G(t)$ − current capacity of FES; $P_A(t)$ − battery power; $P_G(t)$ − external controlled energy source (if any); $P_U(t)$ − known load function (planned consumption schedule); $V(t)$ - state function, the minimum of which is the purpose of optimization. In this case, the power of the PV station is a random function (process); consumer power (load) may also have random deviations (fluctuations). The sign next to the battery power value depends on the charging or discharging process, and the value is determined by the speed. The normalizing factor can be used to select the maximum load P_0, and then all other capacities are taken into account as relative values.

Energy balance (as the cumulative sum of the current power balance for time T will have components:

$$E_V(T,\alpha_x)=E_S(T,\alpha_S)+E_G(T,\alpha_G)\pm E_A(T,\alpha_A)-E_U(T,\alpha_U), \tag{2}$$

where the current value of the accumulated energy $E_A(t, \alpha_A)$, which in absolute value is equal to the state of charge of the battery and is within certain limits (C_{min}, C_{max}). To simplify the presentation of the process can be considered $C_{min} = 0$, and under C_{max} understand the range of charge change. The total balance (2) is zero, provided that the battery charge has not reached the limit value, ie retains the ability to participate in power maneuvering.

Since the recording of the random balancing process is discrete, the power of the imbalance is taken into account in the model as the average values in each elementary (for example, 10-minute) interval Δt, and the accumulated energy is defined as their cumulative sum taking into account the duration of the interval: $E_\Delta(t_i)=\sum_{n=1}^{i} p_i\Delta t$.

The random nature of the level of solar radiation is described by the decomposition of the current power to the average (for example, the average monthly) and random fluctuations within the maximum achievable values for a given region and season [16].

Since solar radiation has a daily cycle, and the average and maximum values are determined, as a rule, for each month, the record of the balancing process is convenient to present in matrix form. The result of taking into account the projected capacity schedule is a random uncontrolled component of deviations from the schedule, which is the subject of modeling and research:

$$p_{ij}=\left[\left(g_{ij}-g_i\right)+\left(s_{ij}-s_i\right)\right]-\left(u_{ij}-u_i\right), \tag{3}$$

where u_x − level of electricity consumption; g_x and s_x − external generation capacity and FES, respectively; i − time index (time interval number); j − number of days. Here p_{ij} − deviation from the load schedule. Indicators with one index − averaged over a certain hour of the day (daily course), in particular u_{and} should correspond to the planned schedule of consumption. Battery charge acts as an intermediate indicator of the internal state of the system.

To assess the efficiency of the use of batteries in the model, it is advisable to use the working volume of stored energy, considering it variable from zero to maximum. The designation for the battery type is written as Cx, where C − full capacity, x − the time in hours required to discharge the battery. It can also be written as kC, where $k = 1/x$ − batteries speed. Really accumulated energy is limited by limit values [0, C] and allowable growth $\delta C = k\Delta tC$, ie determined by the dependence:

$$C_i=C_{i-1}+U(t_i)\Delta t;\ \ U(t_i)\Delta t\le\delta C;\ \ 0\le C_i\le C. \tag{4}$$

Taking into account the energy loss in the battery can be taken into account by introducing the efficiency of the battery KKD: $C_i=C_{i-1}+KKD\cdot U(t_i)\Delta t$.

Taking into account the noted indicators, simulation of random processes of power balancing at different values of the studied parameters is performed, i.e. the process is set in discrete time with a random sequence and the parameters of distribution of simulation results are determined. A further conclusion about the optimality of the selected parameter can be made by constructing the response surface (on the grid of search of the corresponding coordinates) or determining the regression function of the desired parameter on random coordinate values. The coordinates are usually used set capacities or their ratios for the elements of the power system, and indicators of their variability. The studied parameter is the characteristics of energy storage elements (power or capacity) or control elements (balancing capacities). The evaluation criteria can be: indicators of variability of the obtained balance as the degree of predictability of probable situations, or the amount of lost (minimum) or stored (maximum) energy, with the most economical consumption of fuel resources and minimizing the cost of energy obtained. That is, traditionally used technical indicators as a prerequisite for the reliability of the power system, and economic results as desirable conditions.

Block diagram of calculations (Fig. 5) provides for obtaining data on weather factors, their statistical processing, analysis of parameters of the mathematical model for the current electric power of the FES. A similar model applies to load capacity and is based on electricity consumption data for a specific time of year (usually for a particular month). Comparison of generation and consumption modes gives a random component, according to which the characteristics of the battery are selected. The mode of energy storage and consumption includes taking into account the available capacity, speed and energy efficiency of the battery. The result is data on total energy stored (E_{total}) and residual power imbalance, the parameters of the distribution of these random values, which can be used to calculate the reliability indices of the power system.

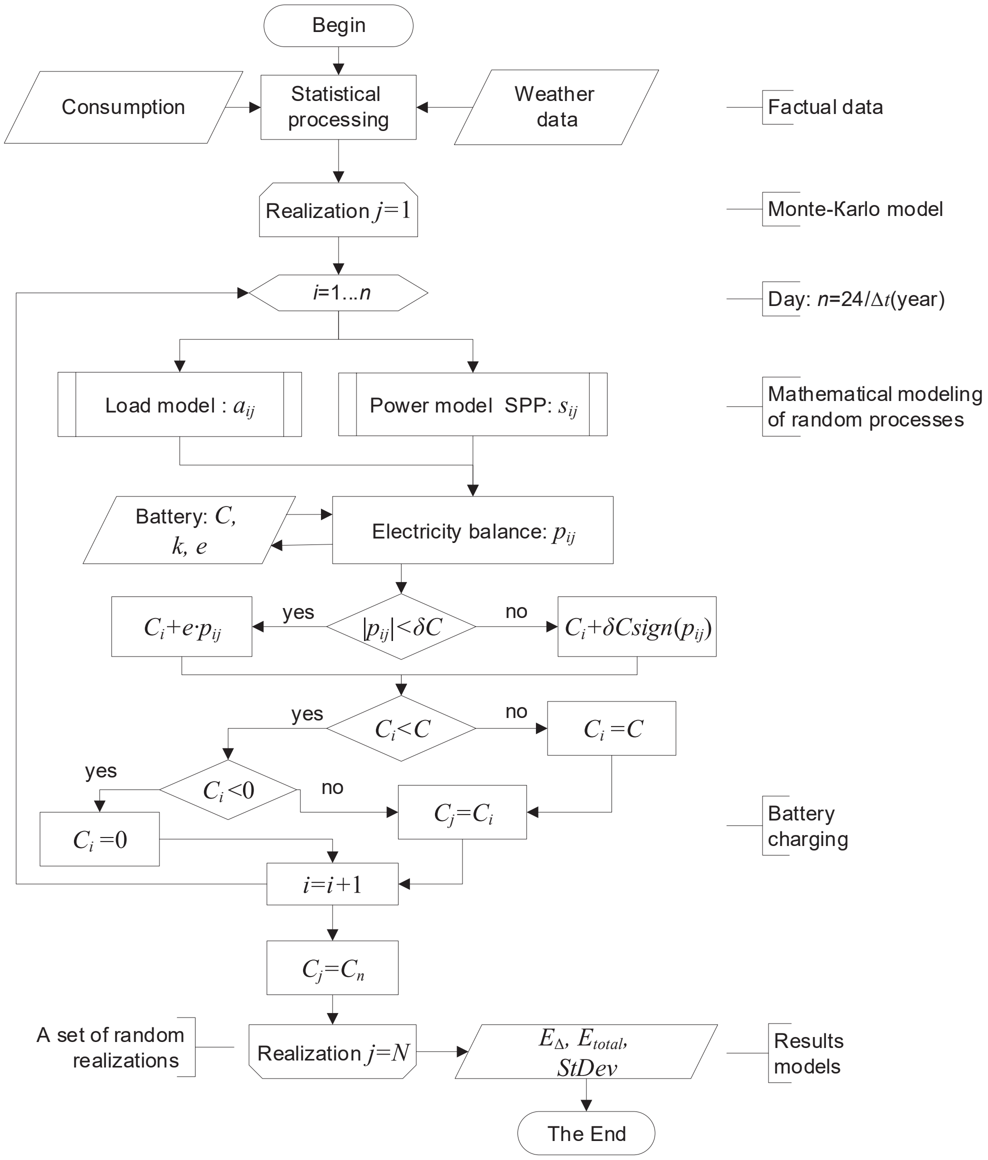

Fig. 5 Block diagram of the calculation of energy balance

The presented algorithm allows to obtain a set of implementations of a random process that describes the balancing of electric energy at random changes of generating and consumed power in the simulated power system, as well as the intermediate accumulation of energy by the storage system. Each individual variant of power system construction includes installed RES capacity, energy characteristics of solar installations, characteristic weather conditions (average values and possible variations), accumulation parameters, accepted restrictions. In this study, each calculation option is represented by several thousand random implementations. The result is a set of data that describes the possible states of the power system and are suitable for statistical evaluation and calculation of the required values. The results of estimates of variability of imbalances of power and energy in the absence of restrictions on the capabilities of batteries are given in Table.

Since the input statistics relate to multi-year data for a particular month (monthly cycle), each individual implementation of the daily average may differ from the monthly average, so as indicators of the variance of the values of the available set of sales are considered rms deviation of the total, i.e. monthly data set - σ_N, as well as the average values of daily variations σ_d, and the daily rms deviation, i.e. the spread of daily averages - σ_{ad}. If the load schedule takes into account the daily forecasting of the expected daily averages (daily cyclicity), it would be assumed that $\sigma_{ad} = 0$, $\sigma_N \approx \sigma_d$.

Table

Dispersion of the general imbalance without the restriction of the batteries

Month	Power balance, acting			Energy storage, acting hours		
	σ_N	σ_d	σ_{ad}	σ_N	σ_d	σ_{ad}
January	0.08	0.068	0.04	0.67	0.37	0.50
April	0.12	0.09	0.07	1.07	0.62	0.80
July	0.09	0.08	0.05	0.65	0.37	0.53

3. Conclusions

The probability distribution for the full set of energy imbalance values (cumulative power sums) is close to normal, although it does not meet all the criteria. The mathematical expectation should be zero due to the accepted assumption of cyclicity. Since during the daily implementation of the random process, the current stored energy can increase many times and return to the system, the nature of the accumulation can be judged by the average daily battery charge level and deviation from the average, with a hypothesis about the distribution density function. When the charging rate is limited within certain limits, the battery discharge also slows down. As a result, the average charging level is maintained. However, the possibility of accumulation of excess energy decreases the more, the lower the speed.

The need for accumulation to ensure a reliable energy balance significantly (at times) depends on the ability to predict the generation of RES, which forms a planned schedule of load on the power system. The energy efficiency of batteries, i.e., the level of losses in the conversion of energy types, should be considered when determining the need for useful capacity. However, proper consideration in this model allows only a linear representation of energy processes. Analytical study of a set of interconnected random processes is impossible without an accurate description of random parameters because these parameters themselves are dynamic quantities, and their evaluation depends on the available finite sample of data. Qualitative behavior of processes can be described by mathematical modeling, and the simulation model estimates numerical values. An accurate description of the dynamic processes of energy accumulation and reuse requires further research.

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