Automated power supply control system for a food industry enterprise using a photovoltaic plant and energy storage

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Abstract

Introduction. Studies were carried out on the power supply control process of a food industry enterprise using a photoelectric plant and electric energy storage to ensure the efficiency of transmission and use of electrical energy.

Materials and methods. The studies were carried out using the methods of modern theory of automatic control and system analysis of control processes.

Results and discussion. The main stages of the power supply control process using a photovoltaic plant and an energy storage system are defined: basic control functions – registration of electric energy consumption, forecasting of electric energy generation using a photovoltaic plant, forecasting of electric energy consumption, determination of parameters of the electric energy storage system, analysis power supply system modes; conditions for providing control functions – information on solar radiation; data on electric energy generation using photovoltaic plant, data on electric energy consumption, limitations and tariffs for electric energy, requirements for the accuracy of forecasting electricity consumption and generation of electric energy using photovoltaic plant, data on energy storage system (current charge, maximum and minimum permissible charges), decision-making on optimization of power supply; organizational and technical mechanisms for the implementation of management functions – information and computing complex, energy dispatcher, chief energy engineer; the database of the electrical supply control system, which is used to prepare decisions; basic information flows that ensure the management of electricity supply – forecast values of meteorological data, current data on electric energy consumption, management actions on the regulation of photovoltaic plant and energy storage system, current data on power supply mode parameters; current data on power supply configuration; control actions on optimization of power supply regimes, management actions on the management of electricity quality indicators; control actions for changing the configuration of the power supply. The functional scheme of power supply control using photovoltaic plant and energy storage system is presented and the requirements for individual units are formulated. The synthesis of the food industry enterprise power supply control system is carried out using the method of ensuring compatibility through sequential integration. In order to ensure energy-efficient power supply of food industry enterprise and optimal use of photovoltaic plant and energy storage system, optimization of modes is carried out using dynamic programming methods.

Conclusion. The development of control systems for power supply of food industry enterprise using photovoltaic plant and energy storage system based on system analysis and compatibility with the use of mode optimization using dynamic programming methods ensures high efficiency of power supply and rational modes of use of photovoltaic plant and energy storage system.

Introduction

The problem of reducing CO_2 emissions, ensuring the reliability of electricity supply and normative indicators of the quality of electric energy, reducing the consumption of electric energy, is relevant for food industry enterprises, as it allows to increase the efficiency of the use of generating capacities, reduce the costs of paying for electric energy and the energy intensity of products that issued by enterprises. To ensure the reduction of CO_2 emissions and electric energy consumption from the network in system of power supply. Food industry enterprise must use photovoltaic plants and electrical energy storage systems, forecast electric energy generation at photovoltaic plants and its consumption at food industry enterprise, and optimize energy storage system and power supply modes.

A number of research are devoted to the issue of power supply management of industrial enterprises using photovoltaic plants and energy storage system.

The method of power supply control using photovoltaic plants and energy storage system to reduce power consumption peaks is presented in Felder et al., 2013. The main idea of the approach is to ensure the efficiency of the power supply by charging the battery only during a fixed period of time. Surplus electric energy generated by photovoltaic plants is stored in battery for a period of time. As a result, losses from the reduction of photovoltaic plants generation may be reduced even without forecasts of photovoltaic plants generation and electric energy consumption. The disadvantage is the impossibility of achieving the maximum degree of electric energy self-sufficiency using photovoltaic plants and energy storage system.

Another way of efficient power supply is by reducing power peaks from the grid (Zeh et al., 2014). The battery charges at a constant rate throughout the day. In order to obtain the maximum amount of energy for the next day, during the period between sunset and sunrise, the battery is discharged at constant power to the lower charge limit. The disadvantage of this method is that the use of this method in the summer months often leads to the active discharge of battery into the network, reducing the self-sufficiency factor. This work also indicates a method of peak smoothing using a battery charged from a solar power plant power peaks. To generate peak smoothing signals, forecasted values of photovoltaic plant power and consumption, as well as iterative methods and linear programming methods are used. The disadvantage of this method is that it does not take into account power losses in the power supply system and the number of battery operation cycles.

Moshövel et al. (2015) proposed a method of ensuring energy-efficient modes of power supply by optimizing the modes of use of the battery by charging it taking into account the state of its charge. The setting for charging the battery is formed depending on the forecast value of the photovoltaic plant power and load. The disadvantage of this method is the impossibility of ensuring energy-efficient modes of the power supply system and taking into account the real state of the battery.

Litjeni et al. (2018) analysed the impact of the forecast on the quality of the system of operational management of electric energy with photovoltaic plants and energy storage system using model-predictive operational in order to minimize the loss from the reduction of electric energy generation of photovoltaic plants. The proposed control method does not ensure the limitation of load peaks from the network and the limitation of the influence of forecast inaccuracies on the modes of the power supply system.

Angenendt et al. (2016) represent an approach to the operational management of the power supply system, which ensures the minimization of losses when reducing the generation of the photovoltaic plants and the optimization of the service life of the battery. The presented method does not ensure the limitation of network load peaks and the optimization of power supply system modes.

Nge et al. (2010) proposed a system of operational management of electricity supply based on priorities. The proposed control system does not provide a high level of self-sufficiency and limitation of network load peaks.

Riffonneau et al. (2009) proposed a deterministic approach to power supply control in order to minimize electric energy costs, taking into account the current capacity of the FES and consumers, variable tariffs for electric energy. The proposed approach does not ensure the optimization of power supply modes and normative indicators of the quality of electric energy.

Park et al. (2012) presented a two-stage operational control method based on priorities to minimize electricity costs taking into account component losses and variable electricity prices. The presented method does not provide a limitation of the peak load of the network, taking into account the real state of battery and electric energy losses in the enterprise network.

Hafiz et al. (2018) develop operational management to minimize operational costs, taking into account variable tariffs for electric energy. The authors show that due to operational control using dynamic programming, it is possible to optimize the size of the battery. However, the method does not ensure high self-sufficiency of the system and taking into account the charge-discharge cycles of the battery.

An et al. (2015) present a method of managing the power supply system using dynamic programming methods and taking into account variable tariffs for electric energy and changes in the battery parameters due to their aging. The disadvantage of the method is that it does not provide optimal methods of photovoltaic plant operation and limits network load peaks.

Ranaweera et al. (2015) developed a multi-stage power supply system control method using photovoltaic plants and consumption forecasts, which takes into account the aging of batteries and ensures the minimization of electricity consumption and the maximum power supplied to the network. The method does not provide high power supply and does not take into account the operating modes of the power supply system.

Keerthisinghe et al. (2014) present a two-stage process of operational control of the power supply system in order to minimize operating costs using mixed integer and dynamic programming systems. The proposed system does not provide an effective level of self-sufficiency and does not take into account changes in the battery parameters due to its aging.

Riffonneau et al. (2011) described a control system that ensures the minimization of electricity costs taking into account the maximum power supplied to the network and taking into account the aging of the battery. The presented method does not ensure high self-sufficiency and consideration of electric energy losses in the elements of the power supply system

Li et al. (2014) proposed a method of operational management of the power supply system, using "fast dynamic programming", which ensures the minimization of operating costs, taking into account the aging of the battery. An analysis of the load power profiles and battery state of charge for individual days and their impact on the control system was performed. The presented method does not ensure the limitation of network load peaks and does not take into account the modes of the power supply system.

The analysis of the considered research showed that the control systems presented in them perform only the battery control function in order to ensure the minimization of electric energy costs, taking into account the battery charge state. However, these systems do not implement the functions of controlling the power supply system using photovoltaic plants and energy storage system as a whole, do not ensure the optimization of power supply system modes and maintenance of standard electric energy quality indicators, which allow obtaining the main economic effect of the system's operation.

The purpose of the research: is to synthesize an automated power supply control system of a food industry enterprise using photovoltaic plants and energy storage system based on a system analysis of the process of managing generation, transmission, distribution and consumption of electric energy, ensuring the sequence of integration and compatibility of individual components.

Materials and methods

Materials

It is considering automated power supply control system for a food industry enterprise using a photovoltaic plant and energy storage system to ensure the efficiency of transmission and use of electrical energy.

Methods

The research was conducted in the following order:

– The tasks of managing the electricity supply of the food industry enterprise with the use of photovoltaic plants and energy storage system are formulated;
– A system analysis of the process of controlling the electricity supply of the food industry enterprise using photovoltaic plants and energy storage system was performed;
– The criteria for managing the electricity supply of the food industry enterprise with the use of photovoltaic plants and energy storage system are formulated;
– A developed algorithm for controlling the electricity supply of the food industry enterprise using photovoltaic plants and energy storage system with the help of dynamic programming;
– A functional scheme for controlling the electricity supply of the food industry enterprise using photovoltaic plants and energy storage system was developed.
– The method of dynamic programming was used to optimize the electricity supply process using photovoltaic plants and energy storage system.

Results and discussion

Recently, there has been widespread use of photovoltaic plants and energy storage system in power supply systems of industrial and civil facilities. The stochastic nature of photovoltaic plants generation, limitations on the state of charge and limitations of battery charge cycles, specific aging conditions of the battery, operation of power supply systems in the conditions of the electricity market of energy (Baliuta et al., 2020) determine the formation of new approaches to the synthesis of power supply control systems of food industry enterprises using photovoltaic plants and energy storage system.

The main approaches to the synthesis of power supply control systems are described in (Baliuta et al., 2018; 2020; Cheremisin et al., 2012; Korolev et al., 2015; Kopylova et al., 2020; Steimle et al., 2006; Zinkevych et al., 2022). The presented approaches to the synthesis of the control system do not allow to take into account: the stochastic nature of electric energy generation, limitations on the charge-discharge of battery, features of power distribution in systems with photovoltaic plants and energy storage system.

Thus, it is necessary to develop food industry enterprise power supply control systems using photovoltaic plants and energy storage system based on system analysis methods that allow determining the main input and output information flows, actions that ensure the formation of the main control functions, information flows that provide control functions.

In addition, it is necessary to formulate the objective function and choose optimization methods that will provide optimal power supply modes for food industry enterprise using photovoltaic plants and energy storage system.

The task of managing the power supply of the food industry enterprise using photovoltaic plants and energy storage system is to minimize the set of technical and economic criteria (Baliuta et al., 2018):

- by the cost of consumed electric energy:

$$F_1(X) = K_w(t) + K_B(t) + K_{PN}(t) \quad (1)$$

K_W represents the criterion of electricity costs, including electricity tariffs k_{EGP} and preferential tariffs k_{FIT}. K_{PN} meets the power supply configuration criteria. If the power P_{Grid}, that is brought up, above the limit $P_{Grid,max}$, K_{PN} increases in proportion to the supplied power. The third criterion K_B takes the effects of battery aging into account.

– for power (energy) losses in the enterprise's electrical network, arising as a result of reactive energy flows:

$$F_2(X) = \sum_{j=1}^{M}\sum_{i=1}^{I_j}\{[Q^2(t) - \sum_{g_{ij}=1}^{G_{ij}} Q_{g_{ij}}(t) h_{g_{ij}}]\} R_{ij} \Big/ U_{ij}^2(t)\ ; \quad (2)$$

with limitations:

– by the active load of the enterprise:

$$\sum_{i=1}^{I_1} P_{enterprise}^{C}(t+t^*) - \sum_{j=1}^{J}\sum_{i=1}^{I_j} P_{enterprise_{ij}}^{C}(t+t^*) k_{ij} \le P_{limit}\ ;$$

– by reactive load of the enterprise:

$$Q_{\min}(t) \le \sum_{i=1}^{I_1}[Q_{enterprise}^{C}(t+t^*) - \sum_{g_{j1}=1}^{G_{i1}} Q_{gi_1}(t) h_{g_{i1}}] \le Q_{\max}(t)\ ;$$

– by to the voltage on the receivers of electrical energy:

$U_{ij\min} \le U_{ij}(t) \le U_{ij\max}$; (5)

– by to the parameters of the quality of electric energy:

$$\delta U_y \le \delta U_y^{(norm)}; \quad (6)$$

$$\delta U_t \le \delta U_t^{(norm)}; \quad (7)$$

$$k_{U2} \le k_{U2}^{(norm)};\ \ k_{U0} \le k_{U0}^{(norm)}; \quad (8)$$

$$k_U \le k_U^{(norm)}; \quad (9)$$

$$k_{U(n)} \le k_{U(n)}^{(norm)}; \quad (10)$$

where $\delta U_y, \delta U_t$ - fixed deviation and voltage change range; k_{U2}, k_{U0} - coefficients of asymmetry in reverse and zero sequences; $k_U, k_{U(n)}$ - distortion coefficients of the sinusoid and the n-th harmonic component of the voltage curve.

System analysis of process of controlling electricity supply food industry enterprise using photovoltaic plants and energy storage system

Electricity supply management in the form of a subsystem is a part of the automated control system food industry enterprise and determines the effectiveness of its electricity supply.

The process of managing organizational and technical objects at the theoretical-multiple level can be represented in the form of reflections of individual actions (Baliuta et al., 2018).

$$C_k : \{M \times G \times Y \times T_{en}\} \rightarrow T_{au}, k = \overline{1, K} \quad (11)$$

where: T_{en} i T_{au} – sets of incoming and outgoing information flows; $T = T_{en} \cup T_{au}$ – actions to form possible combinations of the main information flows; M – actions to form the main management functions; G i Y – accordingly, actions on the formation of possible combinations of mechanisms for the implementation of control functions and basic conditions.

The following information is used and the following actions are performed during the process of controlling the electricity supply of the food industry enterprise using photovoltaic plants and energy storage system:

Information used to ensure the formation of basic conditions for implementation of control functions:

G_1 - data on power schedules and electric energy costs for food industry enterprise (normative acts); G_2 – tariffs and restrictions on electric energy contained in the contract for the supply of electric energy on food industry enterprise; G_3 – requirements for the accuracy of metrological forecasts; G_4 - requirements for the accuracy of the electricity consumption forecast; G_5 - requirements for the accuracy of the generation forecast of electric energy of photovoltaic plants; G_6 - data on the state of the battery of energy storage system; G_7 - data on the evaluation of the effectiveness of the use of photovoltaic plants and energy storage system; G_8 – data on requirements for quality indicators of electric energy; G_9 – the order of interaction of the control system with the database management system; G_{10} – data on the evaluation of the regime energy storage system.; G_{11} – data on the evaluation of the regime of photovoltaic plants; G_{12} – data on the evaluation of the regime of energy storage system.

Actions ensuring formation of main control functions:

M_1 – verification of measurement data for reliability; registration of electric energy received from the network, generated by the photovoltaic plants, accumulated in the energy storage system, consumed by the power supply; registration of the state of the electrical network of food industry enterprise and indicators of the quality of electric energy; M_2 - choice of model and forecasting of consumption of electric energy by food industry enterprise; M_3 - choice of model and forecasting of electric energy generation by photovoltaic plants; M_4 - choice of model and forecasting of the state of the energy storage system; M_5 – analysis of the electrical network configuration; calculation of power supply mode and parameters of electric energy quality; M_6 - formation of a database for controlling the electrical consumption of food industry enterprise and maintaining it in an up-to-date state; M_7 – formation of decisions regarding: electric energy consumption from photovoltaic plants, energy storage system and electric network; delivery of electric energy from photovoltaic plants (energy storage system) to electric networks; the maximum power consumption of the food industry enterprise; M_8 – formation of decisions on optimization of power supply operating modes, choice of electrical network configuration, increase of indicators of the quality of electric energy; M_9 – forming decisions regarding the capacity generated by the photovoltaic plants; M_{10} – formation of decisions regarding the power received from energy storage system.

Main elements and mechanisms that implement control functions:

Y_1 – information on the status and regimes of the power supply, which is provided by the information and computing complex of the chief energy service; Y_2 – restrictions on the configuration of the electrical network, the implementation of power consumption standards, power supply operation modes; indicators of the quality of electric energy, which are formed by the energy dispatcher; Y_3 – restrictions on meeting the requirements of the power system and the reliability of electricity supply, which are formed by the chief energy engineer; Y_4 – data on consumption and capacity of electric energy, generation of electric energy by food industry enterprise, charge energy storage system, quality parameters of electric energy, state of power supply elements and power supply configuration provided by sensors; Y_5 – information for the preparation of decisions on power supply management, which is provided by the database of the American Chemical Society (ACS).

Main information flows that provide control functions:

T_1 – forecast values of air humidity, illumination and ambient temperature coming from the weather station; T_2 – data on the current consumption of electric energy by food industry enterprise; T_3 – current data on the volumes of products produced by divisions and the enterprise; T_4 – restrictions on the volumes of electric energy and power from the power system; T_5 – current data about the ambient temperature; T_6 – forecast values of consumption electric energy on food industry enterprise; T_7 - expenditure plan electric energy for the food industry enterprise; T_8 - making a decision on electric energy expenses; T_9 – management actions to regulate electric energy costs; T_{10} – data on current indicators of the quality of electric energy; T_{11} – data about the current mode parameters of power supply; T_{12} – data about the current configuration of the power supply; T_{13} – data on indicators of the quality of electric energy management; T_{14} – data on the management of changes in the configuration of power supply; T_{15} – management data on the optimization of regimes of power supply; T_{16} - data on photovoltaic plant management; T_{17} - data on energy storage system management; T_{18} - data on the state of the photovoltaic plants; T_{19} - data on the state of energy storage system, T_{20} – forecast values of electric energy generation by photovoltaic plants.

We will present the results of the system analysis of the food industry enterprise power supply management process in the form of displays of individual actions:

– verification of measurement information for reliability, registration of electric energy consumption, assessment of the state of the electric network and indicators of the quality of electric energy:

$$C_1:\{M_1\times(T_1,T_2)\times G_3\times(Y_1,Y_2,Y_5)\}\rightarrow(T_2,T_4); \tag{12}$$

– model selection and electricity consumption forecasting:

$$C_2:\{M_2\times(T_2,T_3,T_5)\times(G_1,G_3,G_5)\times Y_1\}\rightarrow T_6; \tag{13}$$

– choosing a model and forecasting the electric energy generation by the photovoltaic plants:

$$C_3:\{M_3\times(T_1,T_5)\times(G_3,G_7)\times Y_4\}\rightarrow T_{20}; \tag{14}$$

– choosing a model and forecasting the condition of the battery of energy storage system:

$$C_4:\{M_4\times(T_2,T_{10})\times(G_6,G_{12})\times Y_4\}\rightarrow T_{19}; \tag{15}$$

– analysis of power supply, indicators of the quality of electric energy and power supply reliability modes:

$$C_5:\{M_5\times(T_4,T_6,T_9,T_{10},T_{11},T_{12},T_{13},T_{17},T_{18})\times(Y_1,Y_2,Y_3,Y_4,Y_5)\}\rightarrow T_{10},T_{11},T_{12},T_{18}; \tag{16}$$

– making a decision on the volume of electric energy consumption:

$$C_6:\{M_7\times(T_2,T_4,T_5,T_{14})\times(G_1,G_2,G_{11},G_{12})\times(Y_1,Y_2,Y_3,Y_4)\}\rightarrow T_8,T_9; \tag{17}$$

– decision-making regarding configuration changes, optimization of power supply modes, normalization of indicators of the quality of electric energy:

$$C_7:\{M_8\times(T_9,T_{11},T_{12},T_{18},T_{19})\times(G_{10},G_{11},G_{12})\times(Y_1,Y_2,Y_4,Y_5)\}\rightarrow T_{13},T_{14},T_{16},T_{17}; \tag{18}$$

– formation and maintenance of the electric energy cost management database in an up-to-date state:

$$\begin{aligned}&C_8:\{M_6\times(T_3,T_4,T_7,T_8,T_{10},T_{11},T_{12},T_{18},T_{19})\times G_9\times(Y_1,Y_2,Y_3,Y_5)\}\\&\rightarrow T_2,T_3,T_6,T_7,T_{10},T_{18},T_{19};\end{aligned} \tag{19}$$

– making a decision on the volume of electric energy generation by photovoltaic plants:

$$C_9:\left\{\begin{matrix}(M_3,M_7)\times(T_1,T_2,T_4,T_5,T_{11},T_{18},T_{19})\times(G_1,G_6,G_{11},G_{12})\\\times(Y_1,Y_3,Y_2,Y_4)\end{matrix}\right\}\rightarrow T_{16}; \tag{20}$$

– making a decision on the volumes of electric energy from energy storage system:

$$C_{10}:\left\{\begin{matrix}(M_4,M_7)\times(T_2,T_4,T_8,T_{16},T_{18},T_{19})\times(G_1,G_6,G_7,G_{11},G_{12})\\\times(Y_1,Y_2,Y_3,Y_4)\end{matrix}\right\}\rightarrow T_{17}; \tag{21}$$

The decomposition of the power supply control system of the food industry enterprise using photovoltaic plants and energy storage system is performed, which provides its presentation and reflects information interaction, conditions and mechanisms.

Approaches to building an automated power supply control system

The purpose of managing the power supply of the food industry enterprise using photovoltaic plants and energy storage system is the efficient (reliable and economical) supply and use of electricity at the food industry enterprise.

Using the decomposition method, the control task is divided into several separate subtasks: the control task of photovoltaic plants and energy storage system; the task of managing the modes of the enterprise's electric network; the problem of voltage regulation and reactive power compensation.

Methods of solving problems of mode control, voltage regulation and reactive power compensation are described in (Baliuta et al., 2018; 2020; Yovbak et al., 2021).

For the control of photovoltaic plants and energy storage system, predicted values of generation by photovoltaic plants and load capacity are used, as well as mathematical models of individual elements (Kuevda et al., 2021; Zinkevych et al., 2022). The goal of optimization is to determine the SOC trajectory on next day, taking into account the goals of "power costs", "offloading the network" and "increased battery life".

The cost function for electrical energy in the food industry enterprise power supply system using photovoltaic plants and energy storage system is as follows:

$$\varphi = K_{wP} + K_{wQ} + K_{AB} + K_{\Delta PN} + K_Z \tag{22}$$

K_{WP} represents the criterion of costs for active electricity; K_{WQ} represents the cost criterion for reactive electricity and power; $K_{\Delta PN}$ takes into account restrictions on active power consumed or supplied to the network; K_{AB} takes into account the impact of battery aging on the efficiency of the energy storage system.

When optimizing the operation of the power supply system with photovoltaic plants and energy storage system, it is necessary to take into account the state of charge (SOC) of the battery of energy storage system, the permissible degree of charge and discharge of the battery of energy storage system, the permissible number of cycles of charge and discharge of the battery of energy storage system.

Initially, the number of complete cycles will be interpreted as costs. Second, SOC dwell time will also be associated with costs. Starting at SOC 50% from €0 costs increase linearly up to SOC limits ($SOC_{Batt,\ min}$ and $SOC_{Batt,}$).

The task of optimization consists in minimizing the objective function J on the time horizon T:

$$\min J = \sum_{n=1}^{T} \varphi(SOC, n) \tag{23}$$

The limitations used in the optimization can be obtained from the features of the lithium-ion battery. To ensure safe battery operation, SOC and P_{Batt} power are limited as follows:

$$SOC_{Batt,\min} \le SOC_{Batt} \le SOC_{Batt,\max} \tag{24}$$

$$P_{Batt,\min} \le P_{Batt} \le P_{Batt,\max} \tag{25}$$

In addition, at high SOCs, many Li-ion batteries show accelerated aging. To overcome these problems, the proposed improved concepts are based on rules, which allows to further unload the grid by reducing the maximum power supplied and obtaining a fully charged battery in the evening. Considering additional criteria such as battery life, variable energy prices, variable feed-in tariffs and load balancing, optimization-based concepts are used. Recently, dynamic programming has been used to solve such multi-criteria optimization tasks. Using this model-based approach, nonlinear equations (such as the SOC-OCV curve) can be easily considered, there are no restrictions on the design of the objective function, and finally, the optimization result is a global optimum depending on the discretization. Referring to the principle of optimality, it is proposed (Bellman, 2010), the optimization task is divided into subtasks. Each sub-problem is solved and then combined to formulate an overall solution.

The weighted sum approach is used to solve the multi-criteria optimization problem. Weighting coefficients are chosen taking into account expert knowledge.

When optimizing by the method of dynamic programming, the cost function g determines the cost of transition from state x[k] to state x[k+1] (Bellman, 2010):

$$J = g(x[N]) + \sum_{k=0}^{N-1} g(x[k], u[k]) \tag{26}$$

The state variable x represents the state of charge of the battery, and the control variable u corresponds to the battery capacity. Costs for the transition g consist of the target functional shares: electricity costs $C_{ELCOSTS}$, maximum input power to the network $C_{P,NET}$, the maximum set power from the network $C_{P,CONS}$, battery capacity C_{CYCLE}, values up to 50% state of charge C_{SOC} and losses in the system C_{COSTS}:

$$g = C_{ELCOSTS} + \delta \cdot C_{P,NET} + \varepsilon \cdot C_{P,CONS} + \lambda \cdot C_{SOC} + \mu \cdot C_{CYCLE} + C_{COSTS} \tag{27}$$

The weighted sum approach is used to solve this multi-criteria optimization task. Weighting coefficients (δ , ε , λ , μ) are chosen taking into account expert knowledge.

Multi-criteria optimization involves solving several optimization problems with different time horizons: current, short-term, and long-term.

Long-term optimization, works with a time horizon of one month. The purpose of this optimization is to coordinate the aging of the battery and ensure its operating conditions (degree of charge and discharge, number of cycles) that optimize the service life of the battery. On the basis of the residual capacity of the lithium-ion battery, the address correction of the short-term optimization is carried out by adapting the weight coefficients of the objective function. This makes it possible to respond to changes in power of photovoltaic plants (PPP) and consumer behaviour, to compensate for unexpected deviations in the aging characteristics of lithium-ion batteries, and to adapt to different economic conditions. In addition, long-term optimization adjusts the parameters of the online simulation model. The basis of this is state diagnostics, the task of which is to identify the model parameters of the online simulation model during operation.

The level of short-term optimization creates the optimal power flow distribution for the power supply system using photovoltaic plants and energy storage system with a time resolution of 15 minutes. This ensures maximum use of solar energy, reduction of power peaks from the grid on the consumer's side, avoidance of power losses from the shutdown of photovoltaic modules, and minimized electricity costs. The observation horizon is within a few hours. Dynamic programming is used to determine the optimal power flow distribution. Re-optimization using model-predictive control allows you to take into account updated forecast information and compensate for the resulting model and forecast errors.

The current optimization shapes the value of the power of the battery depending on the target power of the network and ensures the efficient operation of the entire system. In addition, the limitation of the maximum charging and discharging capacity is ensured. Instant optimization works every second.

To ensure the conditions of operation of the accumulator battery, it is advisable to use a combined approach when choosing an accumulator battery. It should be taken into account that storage batteries are used to reduce (cut off) rapidly changing peak loads of network power and to power consumer loads that change relatively slowly. Thus, it is advisable to use two storage batteries: one storage battery with a large capacity is designed to cover the peak load of the network, and the other storage battery with a large capacity (charge) with a low self-discharge rate and lower installation costs.

Evaluation criteria are defined to assess the functioning of the operational management process and to quantify the impact of the studied setting parameters.

Degree of self-sufficiency k_{SSUFF} determines the share of annual consumption that can be covered by a photovoltaic system. This criterion is directly related to the costs of purchasing electricity. The higher the level of self-sufficiency, the less additional energy needs to be obtained from the grid. As a result, the cost of purchasing electricity is also reduced.

$$k_{SSUFF} = \frac{E_{CONS} - E_{\mathrm{NETWORK}}}{E_{CONS}} \cdot 100\% \tag{28}$$

The coefficient of own consumption k_{OCONS} shows how large a proportion of the self-consumed photovoltaic energy is in relation to the available photovoltaic energy E_{PPP}. The lower the losses during the disconnection of the photovoltaic plants E_{DISPPP} and photovoltaic energy fed into the grid $E_{FROMNET}$, the higher the level of self-consumption.

$$k_{OCONS} = \frac{E_{PPP} - E_{DISPPP} - E_{FROMNET}}{E_{PPP}} \cdot 100\% \tag{29}$$

Reduction losses k_{REDPPP} show how much photovoltaic energy cannot be used. If the maximum feed-in limit is exceeded, the PV plant no longer operates at the point of maximum output power.

$$k_{REDPPP} = \frac{E_{DISPPP}}{E_{PPP}} \cdot 100\% \tag{30}$$

The maximum power consumed from the network $k_{NET,max}$ means the quarter-hour maximum power received from the grid P_{CONS}.

$$k_{NET,max} = \max\left(P_{CONS}\right) \tag{31}$$

Full battery cycle k_{bcycle} is a measure of the use of a lithium-ion battery. It is calculated based on the battery capacity P_{Batt} in relation to the nominal energy density E_{Batt}.

$$k_{bcycle} = \frac{\int \left|P_{Batt}\right| dt}{2 \cdot E_{Batt}} \tag{32}$$

Automated control system of power supply

On the basis of the tasks of controlling the power supply of the food industry enterprise, control tasks and methods of controlling the photovoltaic plants and energy storage system, a functional scheme of the automated control system of the power supply of the food industry enterprise using the photovoltaic plants and energy storage system was developed (Fig. 1).

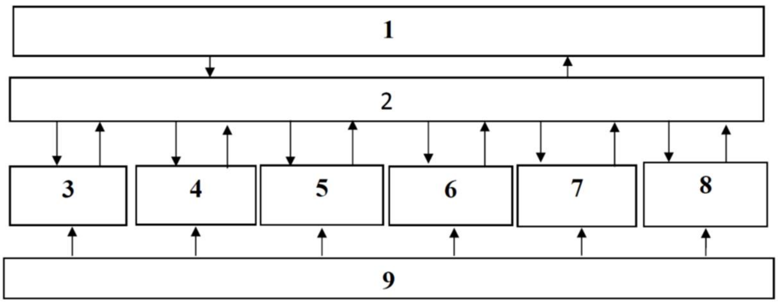

Figure 1. Functional diagram of power consumption and power supply control of food industrial enterprise:

1 – Database of the American Chemical Society of the food industry enterprise energy industry;
2 – Database of control of power supply of food industry enterprise;

3 – Unit for monitoring electricity consumption, electrical loads, generation capacity of photovoltaic plants: automatic transmission of data from electric energy metering devices and control of the reliability of information is carried out;
4 – Block of forecasting of electric load and generation of photovoltaic plants: the forecast (daily, monthly and annual) of food industry enterprise is performed;
5 – photovoltaic plants condition control unit;
6 – Block of control over the state of battery;
7 – Block of optimization of energy supply system modes based on measured values of voltage, active and reactive power;
8 – Block of control of indicators of the quality of electric energy with the help of measuring devices and selection of means of ensuring normative indicators of the quality of electric energy;
9 – Organizational and technical means of controlling the power supply of the food industry enterprise.

It is formulated the requirements for individual functional subsystems (blocks) of the automated control of the power supply of the food industry enterprise based on the performed system analysis.

Functional unit for monitoring electricity consumption, electrical loads, generation capacity of photovoltaic plants

It controls the reliability of information and automatically transmits data from electric energy metering devices, as well as meteorological data. The time interval of reading and transmitting data is determined taking into account the requirements for the accuracy of the calculation of the parameters describing the process of power supply of the food industry enterprise.

Control of the reliability of information at the initial stage involves the analysis of a priori data on the parameters of power supply regimes: permissible limits of parameter changes, the nature of their changes over time, and consistency. Additional reliability control is also carried out, which consists in checking the dependencies between the parameters of the power supply of the food industry enterprise.

Functional unit for forecasting the electric load and generation of photovoltaic plants

The forecast (daily, monthly and annual) of the food industry enterprise load, as well as the electric energy generation schedule from the photovoltaic plants is carried out based on forecast meteorological data. Forecasting is carried out using statistical and intelligent models.

Functional monitoring of the state of photovoltaic plants

On the basis of the automation of information collection and processing, the load of the photovoltaic plants, the parameters of photocells and inverters, the efficiency of their work is estimated, and the parameters of mathematical models are specified.

Functional unit for monitoring state of battery

Based on the automation of information collection and processing, the current charge of the battery, the permissible minimum and maximum charge, the number of permissible charge and discharge cycles, the degree of aging of the battery, and the parameters of the mathematical model are specified.

Functional unit for optimization of power supply modes

With the use of mathematical models based on the values of voltage, active and reactive power measured at the nodal points of the power supply, as well as the network voltage, the capacities of the photovoltaic plants and energy storage system, ensures the formation of rational levels of voltage and losses of electrical energy in the distribution electrical networks of the food industry enterprise.

Functional unit of control of indicators of the quality of electric energy

Based on the indicators of measuring devices installed at different hierarchical levels of the power supply, indicators of the quality of electric energy are determined, using mathematical models, methods of managing technical means of ensuring regulatory indicators of the quality of electric energy are determined.

Appropriate control algorithms are being developed to ensure the functioning of functional blocks.

Organizational and technical means of controlling the power supply of food industry enterprise.

The construction of automated control system power supply of the food industry enterprise is carried out on the platform of a real –time operating system, since it involves the management of food industry enterprise, energy storage system, means of providing indicators of the quality of electric energy in real time. The collection of information and its primary processing is carried out using programmable logic controllers. Programmable logic controllers are distributed at control points and are software compatible with the MS Windows platform.

Construction of automated control system power supply of the food industry enterprise is carried out on the basis of an information model of data, which is built according to the object –oriented principle: all objects of the power supply system, which are control objects in the model are represented by some objects.

Data models are built using CIM (Common Information Model, standard MEK 61968, 61970). This allows you to unify the description of objects, integrate software from different manufacturers within the enterprise, and transfer Common Information Model schemes between applications.

In this way, an approach to the construction of an automated control system for power supply of food industry enterprise using photovoltaic plants and energy storage system is proposed, which involves the creation of a multi –level control system that corresponds to the hierarchical structure of the power supply system, the use of information systems, local and centralized control systems, the application of intelligent control algorithms, and ensures effective use power of photovoltaic plants and energy storage system, as well as achieving high efficiency of the electricity supply system.

The integration of automated control system power supply of the food industry enterprise is carried out by using hardware and software tools that combine disparate functions (accounting of electric energy, voltage regulation, management of power supply modes, management of indicators of the quality of electric energy on the basis of uniform data exchange protocols and communication channels; costs for ensuring their compatibility and interaction and evaluation of the effect obtained as a result of the joint and coordinated functioning of the American Chemical Society.

Conclusion

When creating a food industry enterprise power supply control system, it is advisable to use the decomposition of the control process and methods of system analysis, which allows you to determine the main stages of the management process; conditions for providing control functions; basic information flows that provide power supply control, organizational and technical mechanisms for implementing management functions. In order to ensure effective power supply modes of the food industry enterprise using photovoltaic plants and energy storage system, it is necessary to conduct control based on mathematical models using dynamic programming methods. This will make it possible to make maximum use of the energy obtained from the photovoltaic plants, ensure energy – efficient operation modes of the battery of energy storage system and reduce the peak loads of the network power. The synthesis of the automated control system of the power supply of the food industry enterprise using photovoltaic plants and energy storage system is expediently carried out using the method of compatibility and integration to ensure functional, informational, software and technical integration of system elements. In order to build automated control system power supply of the food industry enterprise, it is necessary to use an information model of the data, built using the Common Information Model information model according to the object – oriented principle.

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