Method for optimizing connection schemes for energy storage devices, taking into account restrictions imposed by the distribution system operator

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Abstract

The increase in the number of renewable energy sources (RES) and customers with unstable consumption parameters increases the need to use energy storage to stabilize the modes of distribution and transmission grids. The instability of RES is one of the key issues that limits their rapid deployment. However, the use of high-capacity electrochemical storage devices allows solving this problem without significant reconstruction of distribution system operators' (DSOs) grids. In order to obtain a positive effect from the introduction of energy storage systems (ESS), their operating modes must be coordinated with the structural and operational limitations of the DSO grids. One of the limiting factors is the energy efficiency of grids, the decrease of which is accompanied by technical and economic consequences for distribution grid operators. This paper presents a method and a specialized algorithm for the placement of distributed energy storage facilities that allow the storage system operator (SSO) to implement system services with a positive effect on distribution grids. We consider the possibility of using energy storage to provide system services at the request of the transmission system operator, as well as to stabilize local operating parameters of distribution grids. The aim of this work is to improve the "ideal" current distribution method and adapt it to solve the actual problem of optimizing the connection schemes of dispersed ESS, taking into account the constraints of electricity distribution systems. It is shown that this optimization problem can be reduced to the problem of calculating currents in a modified substitute circuit of the power grid. Economic factors can be taken into account in the form of fictitious resistances. This approach ensures a smaller number of calculations and high reliability of obtaining a solution close to the extreme.

Keywords

electrochemical energy storage, optimization of connection schemess, distribution grid, power losses, power quality

1. Introduction

The rational use of primary energy resources has become a key factor in sustainable economic growth due to the growing burden on the environment [1]. One solution is to introduce renewable energy sources (RES) to meet the growing demand for electricity while reducing CO_2 emissions. However, the development of solar, wind, and hydro power plants has significantly changed the operating modes of distribution power grids (DPGs) [2]. Therefore, distribution system operators (DSOs) have faced new technical challenges, in particular due to the daily and annual instability of solar and wind power generation [3]. In particular, the adaptation of existing energy infrastructure to ensure reliability, efficiency and environmental sustainability.

Recently, there has been a tendency to develop low-power RES in secondary distribution grids with a voltage of 20-10(6)-0.4 kV and active consumers. Along with its obvious advantages, this has become one of the reasons for non-compliance with voltage quality [4, 5]. Given that with the improvement of

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the investment climate, the number of RES in secondary distribution grids will only grow, and DSOs will be forced to reconstruct these grids to increase their capacity [4]. However, these measures do not eliminate the root causes of the problem. The negative impact of sharply variable load reduces the energy efficiency of existing power grids, and reconstruction measures do not pay off. In addition, the growth of RES capacity and the number of active electricity consumers in distribution networks will be accompanied by an increase in the instability of energy flows, and thus negatively affect the operation of TSOs and the energy market [5, 6].

Another way to solve the problem is to introduce innovative system services based on modern power electronics, in particular, energy storage, which can locally affect the energy efficiency of grids and the quality of electricity [4, 7]. The use of energy storage, in particular electrochemical storage, simplifies the maintenance of energy balance during critical periods of the day and reduces the required generation reserves to ensure the operational security of the power system by reducing peak load [8]. Distributed energy storage systems (DESS) can provide a number of ancillary services, including

- stabilization of energy flows from RES;
- regulation of voltage, active and reactive power flows;
- reactive power compensation;
- optimization of consumer load schedules as part of electricity demand management;
- power reduction at the request of the system operator (an alternative to stabilization outages).

The list of ancillary services provided by the storage system operator (SSO) determines the energy storage technology, the required number of ESSs [9], and the structure of the management system [10]. Therefore, at the level of the DSO, the main optimization task is to form the structure of the storage system and select the parameters of individual installations to provide system services with a minimum return on investment. On the other hand, for the distribution grid operator, to which the ESS is connected, it is important to reduce the negative impact on grid operation due to power fluctuations of unstable sources and variable load, including energy storage, and to improve power quality indicators, especially the voltage profile [11]. These contradictions can lead to complications when concluding contracts for the connection of electrical installations of the storage system operator. Therefore, research on optimizing the integration of energy storage systems (ESS) into distribution grids remains relevant.

2. Literature review

The experience of operating DPGs shows that an alternative to their structural strengthening is the introduction of energy storage systems. In [9], a list of ancillary services that can be provided by the owners of ESSs or storage system operators is given, comprehensive solutions for the implementation of services are proposed, and financial mechanisms for stimulating their development are investigated. It is noted that the tasks of optimizing the placement and management of dispersed ESS modes require special modeling methods. In [10] and other studies, it is shown that electrochemical ESSs are a promising industrial solution due to their flexibility and speed.

Methods for optimizing the connection schemes, design, and nominal parameters of battery storage systems were studied in [11, 12]. In particular, [12] investigates the main trends and technical solutions for the implementation of distributed storage systems. Among the list of issues that have not been resolved is the problem of determining tariffs for specific types of services for SSO, which would contribute to the further development of storage systems. The importance of developing methods and approaches for comprehensive capacity optimization and schemes for connecting dispersed ESSs to distribution grids is noted.

Paper [12] presents the results of a study of economic factors and technical constraints on the integration of ESSs. The optimization criteria and groups of optimization methods for solving individual tasks of a complex problem are detailed. It is shown that in order to obtain a positive effect from the integration of ESSs into distribution grids, it is necessary to take into account design and technical limitations. However, due to the low efficiency of optimization algorithms, in particular heuristic algorithms, it is necessary to develop methods for optimizing the technical and economic effect of integrating storage devices into DSO grids.

Thus, in setting the task of optimizing the integration of ESSs into distribution grids, the factors that determine the efficiency of distribution and quality of electricity, as well as the economic effect for the DSO should be taken into account. For industrial ESS installations, a list of optimized variables that determine the technical and economic efficiency of their connection to distribution grids can be identified, in particular, energy capacity (MWh), maximum power in charge and discharge mode (MW), and grid connection node.

Given the complexity of the complex problem of integrating ESSs, optimization is usually performed by energy intensity, rated discharge power, and grid connection node [11, 12, 13]. Power and energy intensity limitations of the ESS are set based on the investment capabilities of the DSO.

In [13], methods for optimizing the energy intensity and connection scheme of ESSs were studied. In particular, heuristic methods, methods of optimized search for options, methods of mathematical programming, and analytical methods were analyzed. It was found that there is currently no effective solution to the problem of complex optimization of the placement of storages in DPGs.

Thus, the integration and operation of ESSs in distribution grids is accompanied by a number of unresolved issues. In order to achieve a synergistic effect, it is necessary to take into account not only the investment opportunities of DSO, the available list of system services, but also the technical limitations of distribution grids. Therefore, comprehensive optimization criteria should be applied to find effective solutions. When solving problems in this formulation, problems arise with the use of known optimization algorithms.

Based on this, the purpose of this study is to improve the efficiency of distribution grids with integrated ESSs by developing a method for optimizing the energy intensity and connection schemes of individual storage facilities according to a comprehensive technical and economic criterion that takes into account the income from the provision of ancillary services to SSO and the energy efficiency of distribution gridss. The method is based on modeling the “ideal” current distribution [14].

3. Research Results

Problem statement. The problem of optimizing the connection of a dispersed energy storage system to distribution grids can be presented as follows. For a given list of substations with the potential to connect electrical installations, determine the optimal connection schemes for a given list of ESS installations that would ensure the maximum rate of return on investment for DSO by reducing electricity losses. The connection schemes should not limit the control of energy storage devices within their long-term permissible parameters at the request of the SSO, regardless of the distribution grid mode. Therefore, when solving the problem, restrictions are imposed on the voltage profile on substation buses, power transformers and power lines. The modes of individual ESS installations were assumed to be stable for $\Delta t = 30$ minutes. The charging rate was set by the maximum capacity increase over the period Δt. This made it possible to present the optimization problem in the following form:

$$R(\boldsymbol{X}) = \frac{AP(\boldsymbol{X})+DP(\boldsymbol{X})}{K(\boldsymbol{X})} \to min;\ \boldsymbol{X} = |P_i, E_i, L_i,\ i \in [1...n_{ESS}]|;\ L_i \in \boldsymbol{L}; \tag{1}$$
$$E_{i(t)} = E_{i(0)} - \sum_{t \in T} (\eta P^{+}_{Si(t)|t \in \boldsymbol{T_D}} - P^{-}_{Si(t)|t \in \boldsymbol{T_D}});$$
$$D_t = \sum_{i=1}^{n_{ESS}} P^{+}_{Si(t)} - \sum_{i=1}^{n_L} P^{+}_{Li(t)} - \Delta P(\boldsymbol{X}),\ D_t \leq D_{max}, t \in \boldsymbol{T_D};$$
$$C_t = \sum_{i=1}^{n_{ESS}} P^{+}_{Si(t)} + \sum_{i=1}^{n_L} P^{+}_{Li(t)} + \Delta P(\boldsymbol{X}),\ DCt \leq C_{max}, t \in \boldsymbol{T_D};$$
$$E_{i(t)} \leq E_i,\ t \in \boldsymbol{T};\ \boldsymbol{T} = \boldsymbol{T_c} \cup \boldsymbol{T_D};$$
$$|E_{i(t)} - E_{i(t-1)}| \leq \Delta \underline{E_i}(E_{i(t)}),\ t \in \boldsymbol{T},$$
$$P^{+}_{Si(t)} + P^{-}_{Si(t)} \leq P_i,\ i \in [1...n_{ESS}], t \in \boldsymbol{T},$$

$$U_{i\_\min} \le U_{i(t)} \le U_{i\_\max},\ i \in [1...n_{nd}], I_{i(t)} \le I_{i\_\max}, i \in [1..n_{br}] t \in \boldsymbol{T},$$

where $AP(\boldsymbol{X})$ is the annual profit from reducing electricity losses in the grid; $K(\boldsymbol{X})$, $DP()\boldsymbol{X})$ are the capital investments and depreciation charges related to the connection of the ESS; $\boldsymbol{X}$ is the set of potential substations for connection and optimized ESS parameters, in particular, the rated power P_i, capacity E_i and busbar number L_i for connecting the i-th storage device; n_{ESS}, n_L, n_{nd}, $n_b r$ are, respectively, the number of nodes for potential connection of ESS, consumption nodes, voltage-limited nodes, and current-controlled branches; L is the set of potential busbars for connecting storage devices of dimension $n_E SS$; $_{(0)}$, $_{(t)}$ is the energy accumulated by the i-th device at the beginning of the day and at time t; $\Delta \underline{E}$ is the maximum charging rate of the accumulator during Δt; η - is the efficiency of the ESS; ,$P^+_{Si(t)}$,$P^-_{Si(t)}$, $P_{Li(t)}$ is the discharge and charge power of the accumulator and the i-th consumption node during Δt; $\Delta P(X_t)$ is the power loss in power grid during Δt; $\boldsymbol{T_D}$, $\boldsymbol{T_C}$ is the set of periods Δtduring which electricity was accumulated and supplied; D_t, C_t, D_{max}, C_{max} - current and limit imbalances that occur in DPGs during discharge and charge of the ESSs batteries, respectively; $U_{i\_\max}$, $I_{i\_\max}$ - long-term permissible values of voltages and currents in the controlled nodes and branches of the grid, respectively. The technical solutions obtained according to (1) make it possible to take into account the limitations of DSOs and increase their interest in concluding contracts for the connection of such electrical installations.

Solution of the problem. The initial data for solving the problem are the total capacity of the ESS and the range of installations to be connected to the distribution grids, as well as the list of substations to which such electrical installations can be connected. Using (1) and distributing the ESS installations among the authorized substations for each period, Δt specifies the places of their connection and the number of electrical installations for each site. To solve such problems, the method of "ideal" current distribution [14], based on the Hamilton's principle, demonstrates high efficiency. According to this method, for a given period of time, it is quite easy to determine the capacities of electricity sources and consumers (including energy storage) that correspond to a minimum of electricity losses by simulating a certain "ideal" grid mode.

To reproduce it, specific substitute grid schemes (R-schemes) containing only dissipative elements are used [14]. The economic costs associated with the connection and operation of new equipment are taken into account in the R-scheme by additional dissipative elements, the cost of energy losses in which is equivalent to the corresponding costs. The resistances of these elements are determined by economic factors, the current values of the optimized variables X and the parameters of the grid mode [14]. In contrast to analytical optimization methods, this approach significantly reduces the number of calculations, and the solution approaches the global minimum of energy losses, or another objective function presented in the form of equivalent losses [15]. A substitute circuit for simulating the "ideal" current distribution is shown in Figure1. The fictitious resistances R_e ensure that economic factors are taken into account, in particular, investments in connecting storage devices to distribution grids, operating the main equipment, etc.

The formula for calculating and adjusting the economic resistance Re is obtained from the expression for determining the return on investment in connecting ESS (1) using the following sequence of transformations [15]. Since standard solutions are mainly used for connecting electrical equipment to the DPG, the total capital investment K for connecting a given set of EES can be assumed to be conditionally constant. After that, the task of finding the maximum profitability can be reduced to the task of minimising relative operating costs:

$$B = \sum_t \left(\Delta P_{(t)} \Delta t (1 - \alpha_{it}) \frac{C_{(t)}}{K} + \left(\alpha_0 + \alpha_{\Delta W} \sum_{i=1}^{n_H} \Delta P_{i(t)} \Delta t \frac{C_{(t)}}{K} + \alpha_{dc} \right) (1 - \alpha_{it}) + \alpha_{cr} + \alpha_{dc} \right), \tag{2}$$

where $\Delta P(t)$ – power losses in the DPG after connecting the storage device, taking into account its specified operating schedule; $_{(t)}$ – price on the intraday electricity market during the t-th period; K, α_0 $'\alpha_{dc}$ – capital investment for connecting the ESS, relative operating costs and depreciation charges, respectively; $\alpha_{\delta W}$– energy losses of storage devices; α_{it} – income tax; α_{cr} – credit costs.

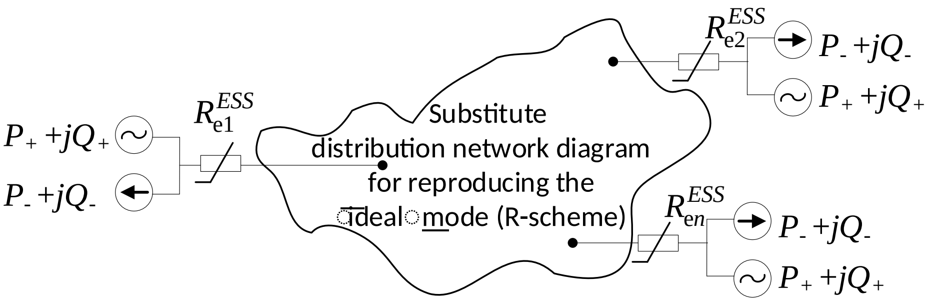

Figure 1: Substitute circuit for simulating "ideal" current distribution with consideration of economic factors.

Using the relative cost of electricity losses $C_{(t)}/K$, the operating costs (2) are transformed into equivalent electricity losses.

$$\Delta W_{equ} = \sum_t \left(\Delta P_{(t)} \Delta t + \alpha_{\Delta W} \sum_t = 1_H^n P_{i(t)} \Delta t + \frac{K}{C_{(t)}} (\alpha_0 + \alpha_{dc}) + \frac{\alpha_{cr} + \alpha_{dc}}{1 - \alpha_{it}} \right) \tag{3}$$

Next, the equivalent losses (??) were converted into 'economic' resistances for a given moment in time t, taking into account the current power of the EES Pi and the voltage module on the connection buses U_i:

$$R_{ci} = \frac{U_i^2}{P_i} \sum_t \left(\alpha_{\Delta W} + \frac{K}{C_t P_{i(t)} \Delta t} \left((\alpha_0 + \alpha_{dc}) + \frac{\alpha_{CT} + \alpha_{dc}}{1 - \alpha_{it}} \right) \right). \tag{4}$$

Since the 'economic' resistance (4) depends on the power of EES $P_{i(t)}$, electricity prices C_t and DPG mode parameters U_i, it will change during the search for a solution. Therefore, the equivalent circuit for simulating "ideal" current distribution must be adjusted from iteration to iteration.

Algorithm for optimizing the connection scheme of ESS installations. For each time interval Δt, the steady-state DPG mode is calculated taking into account the load and generation change schedules. The model of the current grid mode is converted to a linearized one. To simulate the "ideal" current distribution, the distribution grids are presented in the form of an R-scheme. The nodes of the R-scheme corresponding to the substations where ESS units may be connected are assigned the relevant 'economic' resistances (4). The R-scheme nodes located behind the 'economic' resistances are presented as balancing for active power.

According to the results of solving the system of linear equations of the steady-state DPG mode, the current distribution is determined, which corresponds to the minimum power losses for the current DPG mode. Due to the fact that the economic resistances are included in the equivalent grid scheme, the calculated current distribution will correspond to the minimum equivalent energy losses (3), and therefore – the maximum profitability of connecting the storage device (1). Next, the calculated currents in the branches of the equivalent circuit with economical storage resistances are converted into power and the optimal charge/discharge powers of the ESS installation are obtained for the time period t.

Next, the full equivalent scheme of the DPG is used to verify compliance with voltage constraints at grid nodes and current limits of the main equipment. If the restrictions are not met, the parameters of the existing control devices at the substations are adjusted. And only if the control effect is insufficient, the calculated capacities of the storage units are changed under the action of the restrictions. Iterative refinement of the optimization results continues until the increments of the 'economic' resistances for all ESS installations are less than the specified accuracy ϵ. After that, they proceed to the next stage of the daily load schedule of the power system. The obtained data are used to select the storage unit connection nodes, as well as to determine their charge/discharge schedules. These schedules make it possible to determine the number of storage units in the ESS and their design parameters, in particular the optimal capacities that correspond to the solution of problem (1).

Computational experiments. The problem of optimal integration of energy storage devices into the distribution grid (1) was solved using the algorithm given above. The input data were presented in the form of graphs of changes in the energy reserve of ESS and their charge/discharge power, which ensure maximum profit for the storage system operator. An example of such graphs for ESS with a capacity of 40 MWh is given in Figure 2 – Figure 5 for 19.12.24 and 13.04.25. Similar graphs of charge/discharge of ESS were set for the characteristic periods of 2024-2025.

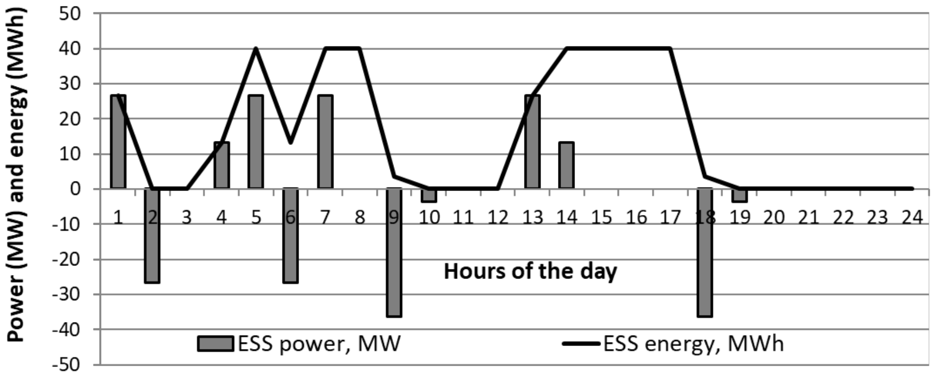

Figure 2: Daily adjustment of power and energy of a 40 MWh ESS at the request of the storage system operator. ESS modes as of 19.12.24.

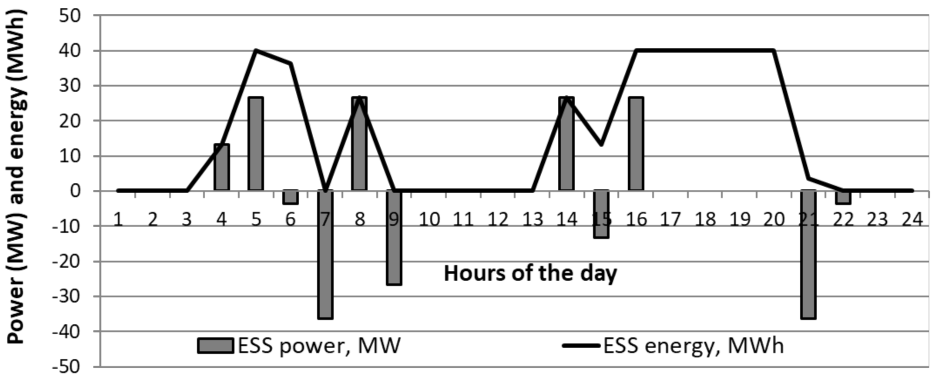

Figure 3: Daily adjustment of power and energy of a 40 MWh ESS at the request of the storage system operator. ESS modes as of 13.04.25.

Further, for each stage of the daily schedule (Figure 2 – Figure 5), the optimal scheme for connecting storage devices to the distribution grid substations was determined. Container-type storage devices with a nominal capacity of 3.8 MWh were used for implementation. The "ideal" current distribution method was used to determine the connection points and the optimal number of storage devices. The results (Table 1) show that due to the consideration of economic factors in the 'economic' resistances of the equivalent circuit, the placement of storage devices depends not only on the sensitivity of power losses in the DPG, but also on the economic aspect. That is why the energy storage systems are algorithmically 'combined' around individual substations, which helps to reduce the costs of their connection and operation. Table 1 shows that these substations have a significant reserve in terms of throughput

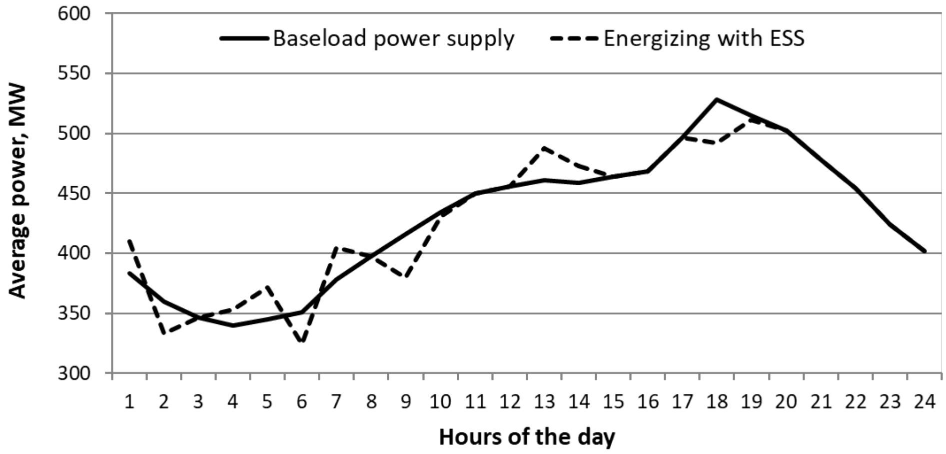

Figure 4: Daily adjustment of power and energy of a 40 MWh ESS at the request of the storage system operator. Electricity supply to DPG as of 19.12.24.

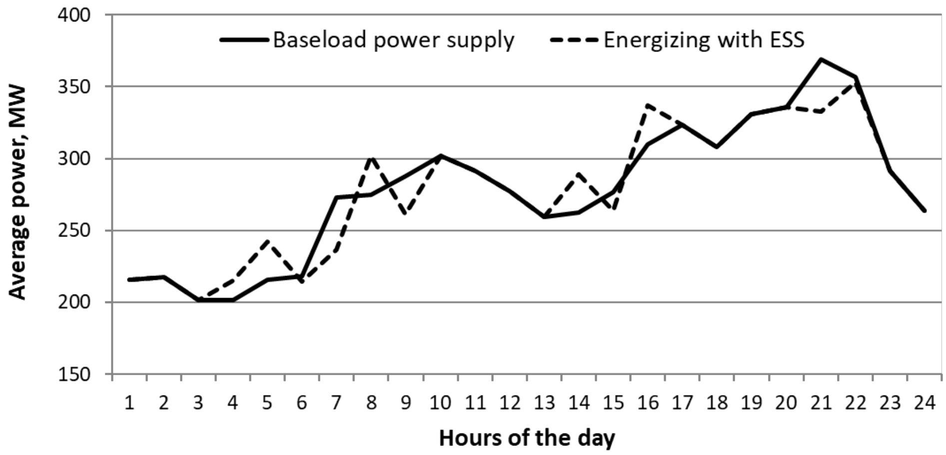

Figure 5: Daily adjustment of power and energy of a 40 MWh ESS at the request of the storage system operator. Electricity supply to DPG as of 13.04.25.

capacity, which is provided by powerful power transformers and a reserve in terms of load capacity.

From the results of the calculations (Table 2), it is evident that efficient integration of the energy storage system leads to a sustained increase in the return on investment, primarily due to the additional income generated by reduced losses in the distribution grids.

4. Conclusions

The integration of energy storage systems into distribution grids is accompanied by an increase in the total charging and discharging capacity of storage devices, which is controlled exclusively by the storage system operator. The uncoordinated use of storage devices during periods of maximum and minimum consumption can cause additional restrictions on the operation of distribution grids. Taking into account the impact of storage devices on DPG modes is associated with certain difficulties. Therefore, an effective optimisation method is proposed to solve this problem.

The charging and discharging modes of ESS installations significantly affect the operating modes of distribution grids, in particular, the current loads of power transmission lines, voltage levels in nodes, and electricity losses. Therefore, taking into account the restrictions of the DSO when optimizing the storage connection schemes is a prerequisite for the formation of effective design solutions. This approach to selecting an energy storage connection scheme can help reduce electricity losses, which is

Table 1
Reliability Indicators of Individual Elements of the Electrical Network

Substation bus section name	Rated transformer power, MVA	Connected load capacity, MW	Loss sensitivity coefficient, MW/MW	Total capacity options for ESS, MWh						
				4	8	12	16	24	32	40
35 kV "Central"	16	9,98	0,040	4	8	8	8	8	8	8
110 kV "Southern"	25	13,76	0,025					8	12	12
110 kV "Southern"	25	12,19	0,023						4	12
110 kV "Chechelnyk"	16	5,16	0,048			4	4	4	4	4
110 kV "Yampil"	10	5,22	0,044				4	4	4	4
Expected reduction in electricity losses, MWh/year				262	518	770	1020	1503	1965	2409

Table 2
Results of Assessing the Economic Effect of Energy Storage System Integrating into Distribution Grids, Taking into Account the Reduction in Electricity Losses

Indicator	Unit	Total capacity options for ESS, MWh						
		4	8	12	16	24	32	40
Reduction in electricity procurement costs	%	0,14	0,28	0,41	0,55	0,82	1,10	1,36
Revenue from reduced electricity procurement costs	k$/year	169,6	339,3	508,8	678,0	1016,5	1355,4	1694,2
Revenue from reduced electricity loss costs	k$/year	35,6	70,5	104,7	138,7	204,4	267,3	327,6
Revenue from ESS integration	k$/year	205,2	409,8	613,6	816,7	1220,9	1622,6	2021,8
Capital investment in ESS	k$/year	1018,1	2036,1	3054,2	4072,3	6108,4	8144,5	10180
ESS maintenance costs	k$/year	81,4	162,9	244,3	325,8	488,7	651,6	814,5
Balance profit	k$/year	123,8	246,9	369,2	490,9	732,3	971,1	1207,4
Depreciation charges	k$/year	101,8	203,6	305,4	407,2	610,8	814,5	1018,1
Payback period	year	4,51	4,52	4,53	4,537	4,55	4,56	4,57

comparable to the implementation of energy-saving measures in distribution grids (Table 2). Therefore, the refinement of optimized variables is accompanied by control of restrictions on the parameters of the DPG mode, which ensures the maintenance of proper energy efficiency of the DSO and the quality of electricity supply to consumers.

Optimisation of the integration of energy storage systems into the grids of the distribution system operator should begin with determining the generalized parameters of the storage system, based on the existing mechanisms of economic stimulation and the volume of SSO investments. After that, the connection of individual ESS installations is optimized, taking into account the restrictions on the part of the distribution system operator. To ensure the energy efficiency of distribution grids and the quality of electricity supply to consumers, this problem is solved using the method of "ideal" current distribution, taking into account active restrictions. If the technical limitations of distribution grids do not allow connecting ESS in full, then their total capacity and the number of energy storage installations can be revised downwards.

For the distribution grids of one of the energy supply companies of Ukraine, optimal schemes for connecting ESS installations with different total capacities were determined. It was shown that without taking into account the influence of the operating modes of electricity storage on losses in distribution grids, the return on investment rate is about five years. Taking into account the additional profit of the energy supply company contributes to reduction in the payback period of capital investments.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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