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Coordinated Operation Strategy of Energy Storages with Reactive Power Compensators in Joint Active and Reactive Power Market Environment

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Abstract: With the ongoing integration of renewable energy and energy storage into the power grid, the voltage safety issue has become a significant challenge for the distribution power system. Therefore, this study proposes a coordinated operation for energy storage systems with reactive power compensators. Taking into account the benefits of energy storage equipped with reactive power compensators and the market clearing process, a bi-level optimization model is formulated. In the proposed model, the upper-level model formulates the bidding strategy for energy storage and aims at maximizing the energy storage revenue; the lower-level model carries out a market-clearing process that takes into account various constraints for ensuring the safe operation of the grid. Afterward, by applying several math tricks such as the KKT optimality condition, the strong duality theorem, and the big M method, the bi-level equilibrium programming problem is transformed into an equivalent and tractable single-level mixed-integer linear programming problem. The results show that the coordinated operation of energy storage and reactive power compensators increases the benefit of energy storage by 3.47%. The benefit increment and security improvement brought by the collaborative operation of energy storage and reactive power compensators are verified.

Keywords: energy storage; reactive power; electricity market; bi-level optimization; bidding strategy

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1. Introduction

Against the backdrop of the promotion of energy strategy and the construction of the electricity market, the large-scale and continuous integration of renewable energy, mainly wind and solar power, and flexible resources, mainly energy storage, into the power grid has brought enormous potential for the economic and low-carbon operation of the power system. Nevertheless, the safety operation risks of the power system come with it. It is particularly important to maximize the benefits of various entities and fully leverage the synergy of resources on a foundation of achieving secure operation of the power grid.

To fully leverage the potential flexibility of energy storage, the role in the power system can be reflected by participating in different markets. Existing literature has extensively studied the markets in which energy storage participates, mainly focusing on the energy market and auxiliary service market. The revenue from the market is closely related to the market's load demand and electricity prices [1,2]. Energy storage can gain profits in

the energy market by utilizing market price differentials through energy trading strategies of low-priced charging and high-priced discharging [3,4]. However, due to the high investment cost of energy storage, relying solely on the arbitrage of market price differences is not enough to effectively incentivize energy storage to actively participate in market operations [5]. Compared to participating in a single energy market, energy storage has more sources of revenue in a joint market. Joint optimization of energy market arbitrage and rapid adjustment ancillary services has been studied in [6], significantly enhancing the income of energy storage and leveraging its excellent regulatory performance. Moreover, the capacity market [7], reserve market [8,9], and participating in the market as a shared energy storage [10,11] are also considered. In addition, some scholars have also explored the reactive power ancillary services market. An incentive mechanism for the reactive power market was proposed in [12,13] to alleviate voltage issues caused by the connection of distributed generation into the grid. Furthermore, the joint optimization scheduling of active and reactive power markets was studied in [14–16].

In China's electricity market, the reactive power market has not yet been established. Therefore, existing operation strategies for energy storage often consider coordination with active power equipment, such as the coordinated operation of energy storage with wind farms [17] or cooperation with traditional generators [18]. However, energy storage primarily participates in the distribution grid. With the increasing number of distributed resources, voltage control issues are becoming more prominent, and the reactive power impact on the grid's safe and stable operation cannot be overlooked.

As the proportion of energy storage in the market gradually increases, gaining revenue in a highly competitive market environment has received significant attention. Existing literature has studied the bidding strategies for energy storage participation in the market. Based on the impact of energy storage on market clearing prices, it can be classified as either a price taker [19–21] or a price maker [3,22–24]. Price takers mean that the operation of energy storage does not affect market prices, allowing energy storage to schedule its output based on predicted market prices [19]. Energy storage can generate revenue in the market through quantity bids or price–quantity bids [20]. With the continuous enhancement of the market power of energy storage in the market, the bidding strategy of energy storage will have an impact on the clearing price of the market. The latter can generate higher revenues than price takers, but it also carries higher risks. As price makers, bi-level game models [23–25] are used for the bidding strategies of energy storage, considering the mutual influence between energy storage and the lower market. Through continuous iterative optimization, a win–win situation for both energy storage and the lower market is achieved.

In most cases, energy storage systems find it difficult to obtain grid information from the distribution network. Therefore, in the interaction process with the superior market, it only connects to the transmission grid as a node, simplifying the network structure and ignoring its network topology information. To solve this problem, a calculation method for nonlinear power flow is proposed in [26]. However, the computation of nonlinear power flow brings great difficulties to the solution. In [27], a linearized power flow method is proposed to model power grid nodes' voltage, phase angle, and line power flow. The linearized power flow method of [27] is used in [28] to consider the influence of network topology and proposes a bidding strategy for virtual power plants with multiple distributed resources in the wholesale market and ancillary service market. To ensure the grid operates safely and economically, it is essential to consider network topology when formulating bidding strategies for energy storage.

In summary, there are still areas for further improvement in existing research: first, most of the studies [17,18] are biased toward the cooperation of energy storage and ac-

tive equipment to participate in the energy and ancillary services market through market bidding strategies and consider less the cooperation with reactive power devices to participate in market bidding. Second, due to the imperfect establishment of China's market, in practice, energy storage participates more in a single market [3,4], such as the energy market or ancillary services market, and the economy and enthusiasm for energy storage as a high-quality regulatory resource to participate in the market have not been fully stimulated. In light of this, this paper comprehensively considers the network topology of the power grid and proposes a trading strategy for energy storage participating in the market that considers the coordination and cooperation of energy storage and reactive power compensators. The main innovations and contributions of this article can be summarized as follows:

(1) A market model considering the joint participation of energy storage and reactive power compensators has been established. This model fully considers the coupling relationship between active and reactive power at the distribution network level and studies the influence of reactive power distribution on active power scheduling.
(2) A distribution side market trading strategy considering network topology security has been proposed. By considering topological security, establishing a joint clearing model with multiple constraint conditions, and coupling relationships between multiple market products, the clearing model becomes more practical.
(3) The strategy proposed in this article for configuring reactive power compensators for energy storage enhances the flexibility of energy storage operation and the safety operation flexibility of the distribution network. The reflection of the incremental benefits of energy storage income from reactive power compensation devices provides a theoretical basis for the operation mode of reactive power compensators for energy storage configuration.

The following is the organization of the rest of this article: The electricity market operation modes are introduced in Section 2. The bi-level optimization model is presented in Section 3. The solution of the bi-level model is introduced in Section 4. Case studies and conclusions are provided in Sections 5 and 6, respectively.

2. Preliminary Knowledge for Electricity Market Operation

In order to further promote the participation of energy storage in the electricity market, the National Energy Administration issued the "Notice on Further Promoting the Participation of New Energy Storage in the Electricity Market and Dispatch Application" in May 2022. However, the operational mechanism of China's spot market is still not perfect. Regarding the energy market and ancillary service market, in terms of market rules, currently, China's Shandong Power Grid (Shandong Province, China) [29] and Southern Power Grid (starting with Guangdong Power Grid) (Guangdong Province, China) [30] mainly adopt a coordinated operation mechanism of clearing two markets in sequence. Compared with CAISO, ERCOT, MISO, and NYISO, which adopt a joint clearing mechanism of spot electricity energy and frequency regulation ancillary service market, sequential clearing cannot obtain the overall optimal plan arrangement of the market, which in turn affects the participation of energy storage in the energy market and ancillary service market [31]. At the same time, in terms of incentive mechanisms for energy storage to participate in the market, due to the lack of corresponding incentive policies, as a high-quality regulatory resource, the market regulation potential of energy storage has not been fully stimulated, and the economy and enthusiasm for participating in the energy market and auxiliary service market are limited. In short, the imperfect operation mechanism of China's spot market will affect the participation enthusiasm and economic benefits of energy storage in terms of rules and incentives, thereby weakening its role in energy arbitrage and ancillary services.

In this paper, energy storage is regarded as an independent entity that declares charge and discharge plans to participate in energy arbitrage and related auxiliary services [32]. This paper combines the trading mechanism of the typical power market in foreign countries [33] and the pilot power market in China [34] and systematically describes the joint operation business model of the electricity energy–auxiliary service market after the intervention of energy storage and reactive power compensation equipment. The market structure is in Figure 1. Market participants mainly include the following three categories: energy storage agents, power market trading centers (distribution system operators), and traditional generation unit operators. To ensure the efficient operation of various market entities and the secure operation of the grid, traditional units and newly configured reactive power compensators provide the reactive power required for system operation, while energy storage does not participate in the provision of reactive power in this paper. Additionally, it is assumed that the energy storage and reactive power compensators are located at the same node in the grid. All market products can be traded through the distribution-level control center, and the electricity trading products discussed in this paper include active power, frequency regulation capacity, and frequency regulation mileage.

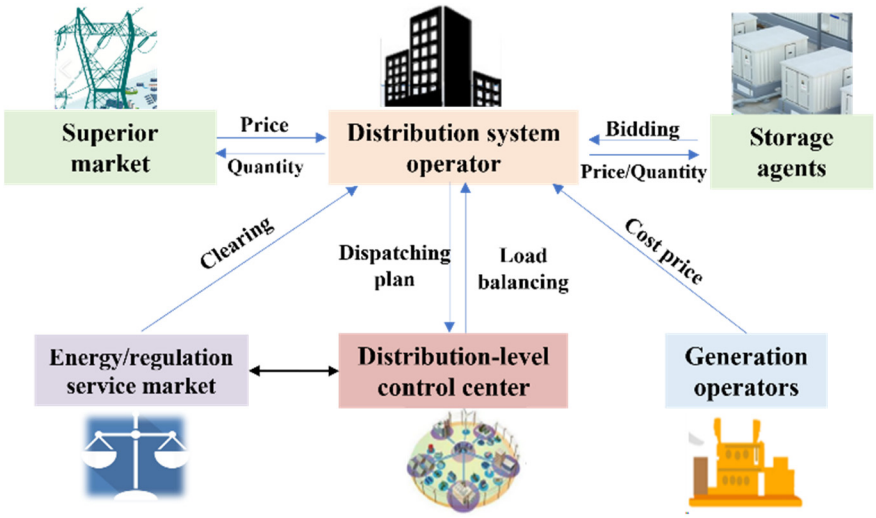


Figure 1. Business model of energy storage participation in the distribution-level electricity market.

It must be made clear that the ownership of the reactive power compensators belongs to the market participants (e.g., energy storage, etc.). The flow of reactive power and active power in the distribution network affects each other, and there is a strong coupling relationship. In view of this, to further promote the economy and enthusiasm of energy storage to participate in the market, this paper studies the bidding strategy of energy storage with reactive power compensators in the electricity market and studies the role of reactive power compensators in promoting the bidding income of energy storage in the market. Also, the commercial operation mode of energy storage with reactive power compensators participating in the distribution-level electricity market can be delimited in the following stages of the process.

(1) Market bidding. In the day-ahead market, the power trading center publishes the next day's load forecast curve, indicating the demand for market products at various nodes. Market participants such as energy storage and traditional units submit their bidding plans based on their own operational status and formulate their strategies or price incentive methods accordingly. To maximize their participation in the market, energy storage with reactive power compensator agents often bid at either zero price

or a significantly higher price. Similarly, conventional power generation operators submit their output ranges and cost characteristics to the power trading center.

(2) Market clearing. The power market trading center collects bidding information from all market entities, takes into consideration the output ranges and cost characteristics of the various participants, and then clears the day-ahead energy and ancillary services market based on the demand for multiple market products and system operation safety constraints. In the process of market clearing, energy storage provides active power, while reactive power compensators provide reactive power based on reactive power demand, achieving voltage support in the region. Through market clearing, market participants receive the winning quantities and clearing prices for each time of the day-ahead market as the basis of its day-ahead market settlement. Additionally, the dispatch plans for each time are sent to the distribution system control center.

(3) Market settlement. The power market operator uses locational marginal prices (LMP) to settle each market participant based on the clearing results of each time in the day-ahead market using time-of-use locational marginal prices. Specifically, energy storage with reactive power revenue is derived from energy arbitrage and the provision of frequency capacity and frequency mileage in the ancillary services market, and considering that the reactive power market has not been established in China, the relevant settlement of the reactive power market has not been considered in the settlement.

3. Modeling of Energy Storage with Reactive Power Compensator Bidding Strategy Based on Bi-Level Optimization

In the distribution-level electricity market, energy storage agents and conventional generator operators jointly act as independent entities participating in electricity market transactions. Each independent entity is concerned about the economic benefits derived from market participation. At the same time, the operational strategy between them is constrained by the system operation constraints. Furthermore, when determining the electricity purchase plan, the distribution-level electricity market trading center takes into account the bidding of various entities to make decisions that are conducive to maximizing social benefits. To cater to the interests and demands of various market entities, a bi-level trading decision model for energy storage, considering the coordination with reactive power compensators, is presented. The framework of energy storage with reactive power compensators that participate in the market is shown in Figure 2.

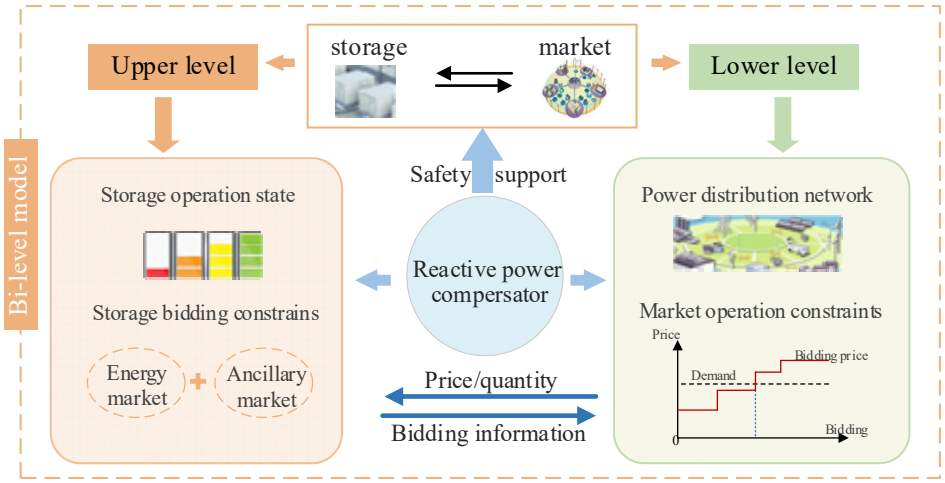


Figure 2. The framework for energy storage with reactive power compensator participates in the market.

The bi-level optimization bidding model proposed in this paper features an apparent logical relationship. First, the upper level takes energy storage with the reactive power compensator as the research object, designs bidding schemes, and transmits them to the lower level. Second, the lower-level model determines the winning electricity quantity and trading price of each market entity by clearing the distribution-level electricity market and conveying them to the upper level. Finally, the upper-level model makes a dispatch plan based on the obtained transaction price and quantities, tracks the dispatch instructions, and calculates the expected revenue for the storage agent.

3.1. Upper-Level Optimal Decision Model of Energy Storage with Reactive Power Compensator

The upper-level model is the trading decision model, in which energy storage with the reactive power compensator formulates bidding strategies based on its own operational status information. In making trading decisions, the primary revenue sources for energy storage are the energy market and the ancillary services market, aiming to maximize combined income from both markets. The objective function is

$$\max F_U = F_p + F_a \tag{1}$$

where F_p is the revenue of the energy market; F_a is the revenue of the ancillary services market.

Due to the different methods by which energy storage and conventional generator sets obtain electricity, energy storage purchases electricity from the power market. Since the construction, installation, and aging costs of energy storage are not considered, the price of electricity from the grid is the charging cost for energy storage when it buys electricity. Similarly, the same applies when energy storage is discharged.

$$F_p = \sum_{t=1}^{Nt} \sum_{k=1}^{N_{BESS}} \lambda_{n,t} \left(p_{k,t}^{d} - p_{k,t}^{c} \right) \tag{2}$$

where N_t is the total running period; N_{BESS} is the quantity of energy storage connected to the power grid; $\lambda_{n,t}$ is the market clearing price of time t at node n in the electricity energy market; and $p_{k,t}^{d}$, $p_{k,t}^{c}$ are the winning bids of energy storage in the market at each moment.

$$F_a = \sum_{t=1}^{Nt} \sum_{k=1}^{N_{BESS}} \left(\lambda_t^{cap} \cdot r_{k,t}^{Ec} + \lambda_t^{mil} \cdot r_{k,t}^{Em} \right) \tag{3}$$

where $r_{k,t}^{Ec}$ is the frequency regulating capacity and $r_{k,t}^{Em}$ is the frequency regulating capacity; λ_t^{cap}, λ_t^{mil} are the clearing price of frequency regulating capacity and mileage in the auxiliary service market.

The operation of energy storage needs to be restricted by corresponding constraints.

(1) During the trading decision-making process, the charge/discharge behavior of the storage cannot be carried out simultaneously.

$$0 \le P_{k,t}^{d} \le \alpha_{k,t}^{d} P_{k,\max}^{d} \tag{4}$$

$$0 \le P_{k,t}^{c} \le \alpha_{k,t}^{c} P_{k,\max}^{c} \tag{5}$$

$$\alpha_{k,t}^{d} + \alpha_{k,t}^{c} \le 1 \tag{6}$$

where $P_{k,t}^{d}$, $P_{k,\max}^{d}$ represent the declared discharge and maximum values of energy storage separately; $P_{k,t}^{c}$, $P_{k,\max}^{c}$ represent the declared charge power and the maximum values of the energy storage; and $\alpha_{k,t}^{d}$, $\alpha_{k,t}^{c}$ are the binary indicators of charging and discharging. These two variables make it impossible to charge and discharge energy storage simultaneously.

During the operation of energy storage, the charging and discharging behaviors of energy storage cannot be carried out simultaneously. In Equation (6), two binary indicators are used to implement this constraint. For non-simultaneous charging and discharging behavior, reference [35] adopts the least-squares approximation approach to transform the nonconvex constraints caused by non-simultaneous behavior into convex constraints, greatly improving computational efficiency. Equations (4)–(6) have already been linearized and are convex in the constraints of the upper-level model, so no relevant transformation is needed.

(2) The operational status constraint of energy storage:

$$S^E_{k,\min} \le S^E_{k,t} \le S^E_{k,\max} \tag{7}$$

$$S^E_{k,t} = S^E_{k,t-1} + \eta^c_k \cdot p^c_{k,t} - 1/\eta^d_k \cdot p^d_{k,t} \tag{8}$$

where $S^E_{k,\max}$ sets the maximum charge states for the secure operation of the storage k and $S^E_{k,\min}$ sets the minimum charge states; $S^E_{k,t}$ is the operational status of the storage; and η^d_k, η^c_k are, respectively, the discharge and charge efficiency. The limitation of the operational status can keep the storage within the safe operating range.

(3) In case energy storage is declared in the joint market, the declaration of various market products needs to meet certain constraints, which are as follows:

$$0 \le P^c_{k,t} + R^{Ec}_{k,t} \le P^c_{k,\max} \tag{9}$$

$$0 \le P^d_{k,t} + R^{Ec}_{k,t} \le P^d_{k,\max} \tag{10}$$

$$0 \le R^{Ec}_{k,t} \le R^{Ec}_{k,\max} \tag{11}$$

$$0 \le R^{Em}_{k,t} \le R^{Ec}_{k,\max} \cdot \delta_{ess,k} \tag{12}$$

where $R^{Ec}_{k,t}$, $R^{Em}_{k,t}$, respectively, are the frequency regulating capacity and frequency regulating mileage declared by energy storage; $R^{Ec}_{k,\max}$ is the maximum frequency regulating capacity of energy storage; and $\delta_{ess,k}$ is the frequency regulating mileage multiplier of energy storage k.

3.2. Lower-Level Joint Market Clearing Model

In the market, the power trading center collects bidding information from various participants and then clears the market. This clearance process involves the joint clearing of the energy and ancillary services markets, enabling optimal allocation of global resources for overall optimal scheduling. The optimization goal of the lower power trading center is to minimize the sum of power purchase costs and auxiliary service costs of the whole market.

$$\begin{aligned} \min F_L \;=\; & \sum_{t=1}^{Nt} \left[b^{up}_t p^{up}_t + b^{upc}_t r^{upc}_t + b^{upm}_t r^{upm}_t \right] \\ & + \sum_{t=1}^{Nt} \sum_{k=1}^{N_G} \left[b^G_{m,t} p^G_{m,t} + b^{Gc}_{m,t} r^{Gc}_{m,t} + b^{Gm}_{m,t} r^{Gm}_{m,t} \right] \\ & + \sum_{t=1}^{Nt} \sum_{k=1}^{N_{BESS}} \left[b^d_{k,t} p^d_{k,t} - b^c_{k,t} p^c_{k,t} + b^{Ec}_{k,t} r^{Ec}_{k,t} + b^{Em}_{k,t} r^{Em}_{k,t} \right] \end{aligned} \tag{13}$$

where N_G is the number of traditional units; b^{up}_t, b^{upc}_t, b^{upm}_t represent the prices of various services such as active power and frequency modulation purchased from the upper market, respectively; $b^G_{m,t}$, $b^{Gc}_{m,t}$, $b^{Gm}_{m,t}$ are, respectively, the power generation cost, frequency regulating capacity cost, and frequency regulating mileage cost declared by generation unit m at time t; $b^c_{k,t}$, $b^d_{k,t}$ represent the prices of various services such as charge, discharge declared by the storage k at time t; $b^{Ec}_{k,t}$, $b^{Em}_{k,t}$, $r^{Ec}_{k,t}$, $r^{Em}_{k,t}$ represent the declared price and the medium scalar in the ancillary service market of storage k at time t; p^{up}_t, r^{upc}_t, r^{upm}_t represent the amount of

electricity, capacity, and mileage purchased from the upper market at time t; and $p_{m,t}^{G}$, $r_{m,t}^{Gc}$, $r_{m,t}^{Gm}$ are the medium scalar of m power, medium scalar of frequency regulating capacity, and medium scalar of frequency regulating mileage of generation units m.

In the process of clearing the electricity market, market members need to meet the relevant rules and constraints.

(1) The power trading center needs to consider the network security constraints in the clearing process.

$$\sum_{m\in\varphi_g(n)} p_{m,t}^{G} + \sum_{k\in\varphi_{ess}(n)} \left(p_{k,t}^{d} - p_{k,t}^{c}\right) - \sum_{d\in\varphi_d(n)} p_{d,t}^{L} + p_t^{up} = \sum_{q\in\varphi(n)} P_L \tag{14}$$

$$\sum_{m\in\varphi_g(n)} Q_{m,t}^{G} + \sum_{k\in\varphi_Q(n)} Q_{k,t} - \sum_{d\in\varphi_d(n)} Q_{d,t}^{L} + Q_t^{up} = \sum_{q\in\varphi(n)} Q_L \tag{15}$$

$$P_L = \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2}(V_i - V_j) + \frac{x_{ij}}{r_{ij}^2 + x_{ij}^2}(\theta_i - \theta_j) \tag{16}$$

$$Q_L = \frac{x_{ij}}{r_{ij}^2 + x_{ij}^2}(V_i - V_j) - \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2}(\theta_i - \theta_j) \tag{17}$$

$$-L_l \le P_L \le L_l \tag{18}$$

$$-Q_l \le Q_L \le Q_l \tag{19}$$

$$V_{\min} \le V \le V_{\max} \tag{20}$$

$$\theta_{\min} \le \theta \le \theta_{\max} \tag{21}$$

where $\varphi_g(n)$, $\varphi_Q(n)$, $\varphi_{ess}(n)$, $\varphi_d(n)$ represent a collection of generation units, energy storage, reactive power compensator, and loads located on node n; $\varphi(n)$ represents all branches connected to node n; $p_{d,t}^{L}$ is the load situation of the grid; $Q_{m,t}^{G}$, $Q_{k,t}$, $Q_{d,t}^{L}$ are the reactive power value of the unit, reactive power compensator, and reactive power load, respectively; r, x represents the resistance and reactance of the lines in the power grid; V, $V_{\max}$, $V_{\min}$ represent the voltage, the max, and the min voltage of the grid node; L_l, Q_l represent the active power and reactive power transmission capacity limits of line l; θ, $\theta_{\max}$, $\theta_{\min}$ represent the phase angle, the max angle, and the min angle of the grid node.

Note that Equations (14) and (15) represent the market demand balance equations of each node of the power network, and the balance equation must be satisfied in order to ensure the security of the network in the process of market clearing, respectively; Equations (16) and (17) use a linearized solution method for power flow calculation of network topology; Equations (18) and (19) reflect the constraints of line active and reactive power transmission capacity values in the network structure; Equations (20) and (21) reflect the constraints of voltage and phase angle in the network structure. Once these constraints are exceeded, they will have an impact on the safe operation of the entire power network.

(2) At any given moment, the supply and demand of ancillary services are always in a state of equilibrium.

$$\sum_{k=1}^{N_G} r_{m,t}^{Gc} + \sum_{k=1}^{N_{BESS}} r_{k,t}^{Ec} + r_t^{upc} = R_t^{c} \tag{22}$$

$$\sum_{k=1}^{N_G} r_{m,t}^{Gm} + \sum_{k=1}^{N_{BESS}} r_{k,t}^{Em} + r_t^{upm} = R_t^{m} \tag{23}$$

where R_t^{c}, R_t^{m} represent the frequency regulating capacity demand and frequency regulating mileage demand of the system.

(3) When various resources in the market reach a supply–demand balance, the winning capacity and winning mileage of energy storage and units must meet the corresponding constraints.

$$P_{\min}^{up} \le p_t^{up} \le P_{\max}^{up} \tag{24}$$

$$p_t^{up} \le P_{k,\max}^{up} - r_t^{upc} \tag{25}$$

$$p_t^{up} \ge P_{\min}^{up} + r_t^{upc} \tag{26}$$

$$r_{\min}^{upc} \le r_t^{upc} \le r_{\max}^{upc} \tag{27}$$

$$0 \le r_t^{upm} \le r_{\max}^{upm} \tag{28}$$

$$0 \le p_{k,t}^{c} \le P_{k,t}^{c} \tag{29}$$

$$0 \le p_{k,t}^{d} \le P_{k,t}^{d} \tag{30}$$

$$0 \le r_{k,t}^{Ec} \le R_{k,t}^{Ec} \tag{31}$$

$$0 \le r_{k,t}^{Em} \le R_{k,t}^{Em} \tag{32}$$

$$0 \le r_{k,t}^{Em} \le \delta_{ess,k} r_{k,t}^{Ec} \tag{33}$$

$$p_{k,t}^{c} \le P_{k,\max}^{c} - r_{k,t}^{Ec} \tag{34}$$

$$p_{k,t}^{d} \le P_{k,\max}^{d} - r_{k,t}^{Ec} \tag{35}$$

$$p_{m,t}^{G} \ge P_{m,\min}^{G} + r_{m,t}^{Gc} \tag{36}$$

$$p_{m,t}^{G} \le P_{m,\max}^{G} - r_{m,t}^{Gc} \tag{37}$$

$$Q_{m,\min}^{G} \le Q_{m,t}^{G} \le Q_{m,\max}^{G} \tag{38}$$

$$0 \le r_{k,t}^{Gm} \le \delta_k r_{k,t}^{Gm} \tag{39}$$

$$0 \le r_{m,t}^{Gc} \le R_{m,\max}^{Gc} \tag{40}$$

$$0 \le r_{m,t}^{Gm} \le R_{m,\max}^{Gm} \tag{41}$$

where $P_{\max}^{up}$, $r_{\max}^{upc}$, $r_{\max}^{upm}$ are the maximum value of power, frequency regulating capacity, and mileage that can be purchased by the distribution-level market from the upper market; $P_{\min}^{up}$, $r_{\min}^{upc}$ are minimum value of power and frequency regulating capacity that can be purchased by the distribution-level market from the upper market; $P_{m,\min}^{G}$, $Q_{m,\min}^{G}$ represent the minimum value of active power and reactive power emitted by the unit m; $P_{m,\max}^{G}$, $Q_{m,\max}^{G}$ represent the maximum value of active power and reactive power emitted by the unit m; $R_{m,\max}^{Gc}$, $R_{m,\max}^{Gm}$ represent the maximum frequency regulating capacity and mileage of the unit m.

Note that Equations (24)–(28) represent constraints on purchasing market products from upper-level markets; Equations (29)–(35) represent the operational constraints that energy storage needs to meet in the energy market and ancillary services market; Equations (36)–(41) consider the coupled operation of traditional power generation units in the energy market and the ancillary service market, which has achieved the output limitation of traditional power generation units.

(4) Capacity constraint of reactive power compensator:

$$Q_{k,\min} \le Q_{k,t} \le Q_{k,\max} \tag{42}$$

where $Q_{k,\min}$, $Q_{k,\max}$ represent the maximum values that the reactive power compensator can provide.

3.3. Pricing Methods for Various Electricity Market Products

The clearing model of the above-mentioned distribution-level electricity market is written in the standard convex optimization form as follows:

$$\min \ = \sum_{j=1}^{N} f_j X(j) \tag{43}$$

$$s.t. \sum_{j=1}^{N} (a_{n,j} X(j)) \leq b_n, \ n = 1, \ldots p \tag{44}$$

$$\sum_{j=1}^{N} (c_{m,j} X(j)) = d_m, \ m = 1, \ldots q \tag{45}$$

where N represents the quantity of all variables after standardizing the market clearance model; x represents the decision variable; and m and n represent the number of equality constraints and inequality constraints in the model, respectively. Note that Equations (44) and (45) are the standard form of inequality and equality constraints in the clearing model.

Based on the above standard model, an augmented Lagrangian function for the clearing problem of the distribution-level electricity market can be written as follows:

$$\begin{aligned} L(X, \mu_n, \lambda_m) = F_L(X) + \sum_{n=1}^{p} \mu_n \Big(\sum_{j=1}^{N} (a_{n,j} X(j)) - b_n \Big) \\ + \sum_{m=1}^{q} \lambda_m \Big(\sum_{j=1}^{N} (c_{m,j} X(j)) - d_m \Big) \end{aligned} \tag{46}$$

where μ_n is the Lagrange multiplier of the inequality constraints; λ_m is the Lagrange multiplier of the equality constraints.

By solving the market clearing problem, the optimal bidding result of energy storage with the reactive power compensator and Lagrange multiplier optimal solution can be obtained. Based on the Envelope Theorem, the Lagrange multipliers corresponding to equation constraints (14), (22), and (23) are the clearing prices of the power market and the auxiliary market, respectively.

4. The Reconfiguration and Solution of the Bi-Level Model

There is a strong coupling relationship between the upper and lower levels of the bi-level model, and the upper-level model also contains nonlinear terms, making it challenging to solve directly. Nevertheless, the problem involved is a linear optimization problem in the lower-level market clearance model. In this case, converting the bi-level model into a single-level model is an effective solution method.

4.1. Model Reformulation

By using the KKT conditions and introducing Lagrange multipliers, the lower-level problem can be transformed into additional constraint conditions for the upper-level problem based on the compact form of the lower-level model, such as Equations (43)–(45); the KKT conditions are written as follows.

$$\nabla_x L = f_j + \sum_{n=1}^{p} \mu_n a_{n,j} + \sum_{m=1}^{q} \lambda_m c_{m,j} = 0 \tag{47}$$

$$\sum_{j=1}^{N} (c_{m,j} X(j)) - d_m = 0, \ m = 1, \ldots q \tag{48}$$

$$\sum_{j=1}^{N}(a_{n,j}X(j)) - b_n \le 0,\ n = 1,\dots p \tag{49}$$

$$\mu_n\left[\sum_{j=1}^{N}(a_{n,j}X(j)) - b_n\right] = 0,\ \mu_n \ge 0 \tag{50}$$

Due to the presence of nonlinear terms in the objective function and constraint conditions, the bi-level model has been transformed into a single-layer Mathematical Program with Equilibrium Constraints (MPEC) model.

In the obtained single-level MPEC model, there are two nonlinear terms, namely the complementary relaxation constraint generated by the KKT condition and the nonlinear term multiplied by two variables in the upper objective function.

(1) Complementary relaxation constraint linearization

The big M method is introduced to solve this problem and address the complementary relaxation constraint nonlinear term in the KKT conditions.

$$\begin{aligned} &0 \le \mu_n \le Mv \\ &0 \le \sum_{j=1}^{N}(a_{n,j}X(j)) - b_n \le M(1-v) \end{aligned} \tag{51}$$

where v is the binary indicator; M is a very large number.

(2) Linearization of objective function

Considering the nonlinear terms in the upper objective function caused by variable multiplication, when handling these terms, according to the strong duality theorem, the optimal value of the lower-level objective function equals the optimal value of the dual problem. The optimal value of the problem can be expressed as:

$$E^* = \sum_{n=1}^{p}(b_n{\mu_n}^*) + \sum_{m=1}^{q}(d_m{\lambda_m}^*) = {F_L}^* \tag{52}$$

where E^* represents the value of the objective function at the optimization of the dual problem; ${F_L}^*$ represents the value of the objective function at the optimization of the original problem; and ${\mu_n}^*$, ${\lambda_m}^*$ represent the optimal value of the Lagrange multiplier.

Accordingly, in accordance with the above content, the upper objective function containing dual nonlinear terms can be transformed into:

$$\begin{aligned} F_{U}\prime \ &= F_p + F_a \\ &= \sum_{n=1}^{p}(b_n\mu_n) + \sum_{m=1}^{q}(d_m\lambda_m) \\ &+ \sum_{t=1}^{Nt}\left[b_t^{up}p_t^{up} + b_t^{upc}r_t^{upc} + b_t^{upm}r_t^{upm}\right] \\ &+ \sum_{t=1}^{Nt}\sum_{k=1}^{N_G}\left[b_{m,t}^{G}p_{m,t}^{G} + b_{m,t}^{Gc}p_{m,t}^{Gc} + b_{m,t}^{Gm}p_{m,t}^{Gm}\right] \end{aligned} \tag{53}$$

Then, the original model is converted into a mixed-integer linear program (MILP) problem, which is Equation (53) and can be directly solved through a commercial solver.

$$\begin{gathered} \text{Max } (53) \\ s.t.\ (4)\text{–}(12),\ (14)\text{–}(15),\ (22)\text{–}(23),\ (47)\text{–}(51) \end{gathered}$$

4.2. Model Reconstruction

The proposed bi-level optimization model for energy storage participating in the market is a linear optimization problem, which means that the lower model can be equivalently transformed into a constraint for the upper-level optimization problem based on the KKT conditions. Then, the bi-level model is converted into a single-level MPEC problem. Considering the nonlinear terms in the transformed model, based on the strong duality theorem and the large M method, this MPEC model is further converted into a MILP problem that can be directly solved. The transformation framework of bi-level models is shown in Figure 3, and the model-solving flowchart is shown in Figure 4.

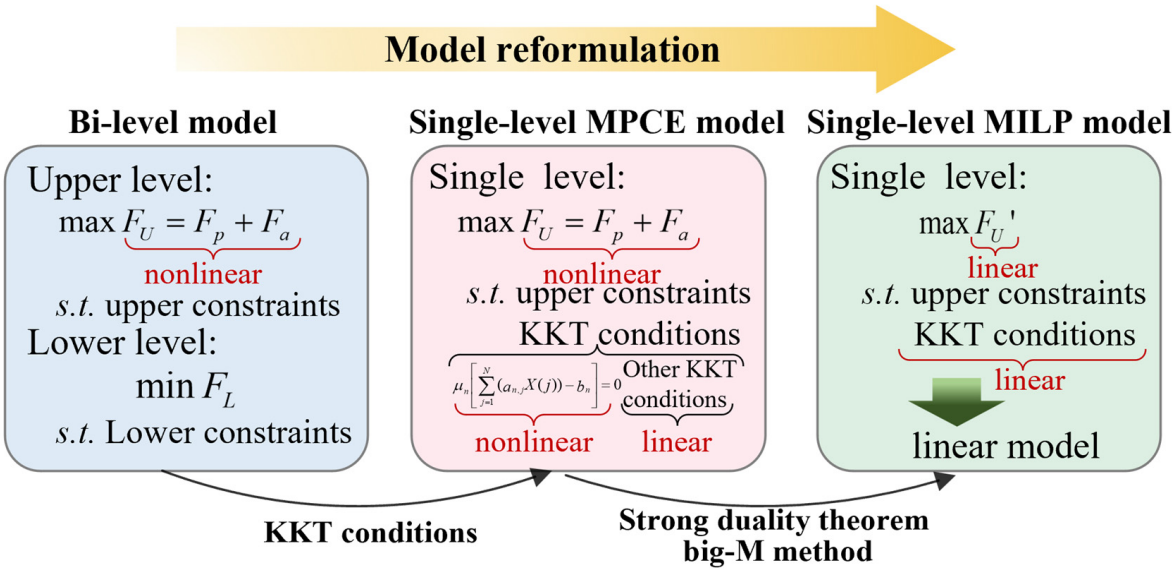


Figure 3. The transformation framework of bi-level models.

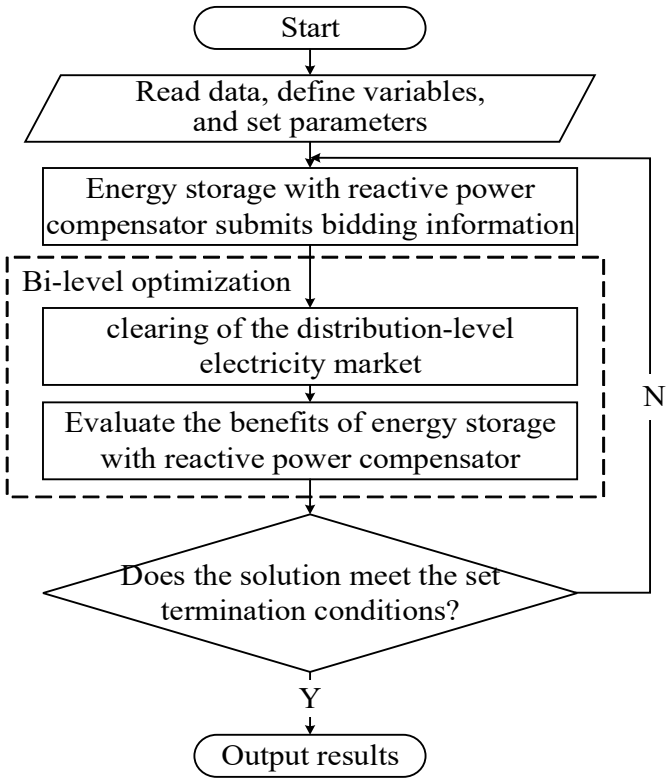


Figure 4. Model-solving flowchart.

5. Case Study

In this part, the method's effectiveness is verified based on the IEEE 33-bus distribution system. Figure 5 shows the overall network topology for testing the proposed method. Figure 6 shows the price curves for the active power market. The active power and reactive power load of each node are proportionally distributed based on the measured curve. Among them, node 1 is connected to the upper market, and the traditional generator G1~G4 is connected to each node in the distribution network, respectively. The parameters of the controllable devices are given in Table 1 the distribution network is allocated with two energy storages, i.e., S1 and S2, and the parameters of S1 and S2 are given in Table 2.

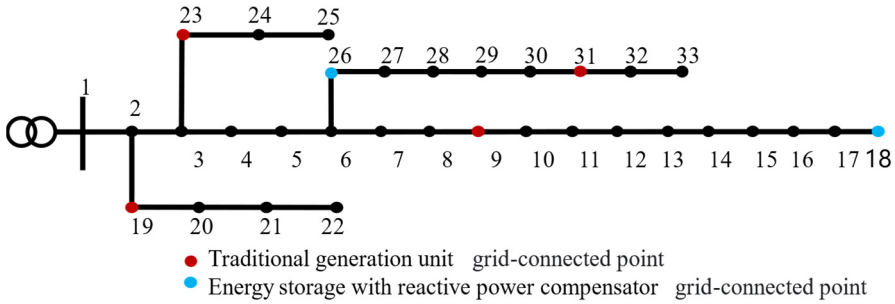


Figure 5. Topology of the 33-bus network.

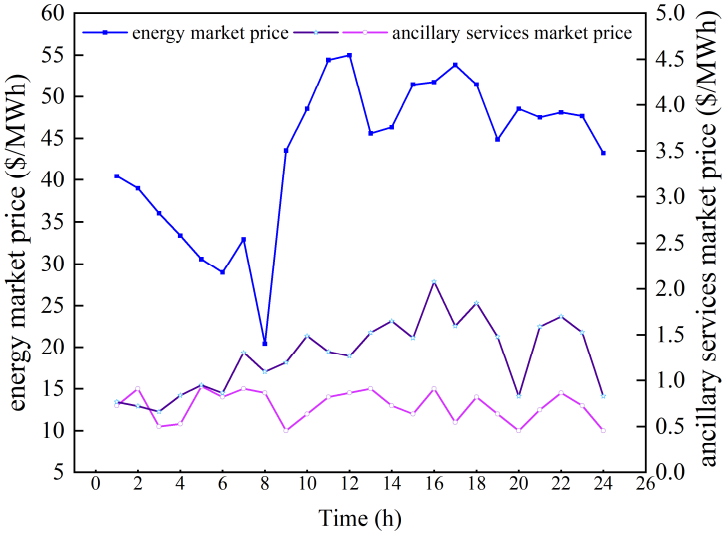


Figure 6. The price curves for the active power market.

Table 1. Generator unit parameter settings.

Parameters	Price (USD/MW)	Pmax (MW)	Ratio	Location of the Node Number
G1	45.67	30	7	19
G2	43.76	20	12	23
G3	48.06	70	10	28
G4	55	60	9	9

Table 2. Energy storage parameter settings.

Parameters	Max Cap (MW·h)	Pmax (MW)	SOCmax/SOCmin	η_k^c/η_k^d	Location of the Node Number
S1	60	20	0.9/0.1	0.95/0.95	18
S2	20	10	0.9/0.1	0.95/0.95	26

5.1. Coordinated Operation Results of Energy Storages with Reactive Power Compensators

This section primarily analyzes the variation in the quantity of the energy storage winning bids before and after the integration of reactive power compensators.

Case 1: No reactive power compensators are added.

Case 2: Reactive power compensators are added.

As shown in Figure 7, there was a significant disparity in the quantity of winning bids between S1 and S2 in the energy market. S2 has a higher participation rate than S1, primarily because S1 is located at the end of the line and is constrained by network topology security constraints. As shown in Figure 8, taking t = 19 h as an example, the system's clearing price is relatively low at this time. S1 should ideally choose to charge during this period to prepare for discharging during high-price periods later. However, due to the low voltage at its node, charging at this time poses a risk of voltage limit violations. To avoid this situation, S1 has to discharge to support the voltage, which prevents it from playing its intended role in market arbitrage later. Consequently, S1 loses part of its economic benefits due to its inability to fully participate in the energy market arbitrage.

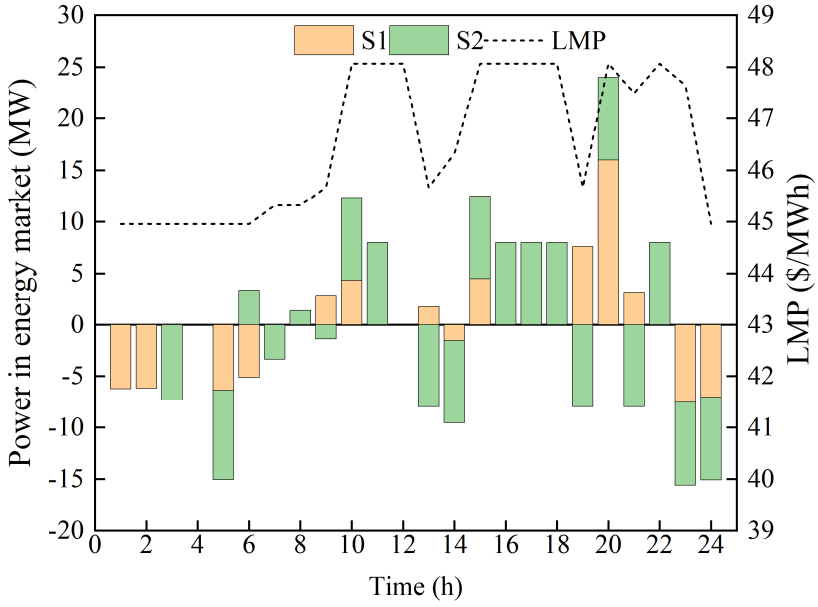


Figure 7. Bidding in the electric energy market of case 1.

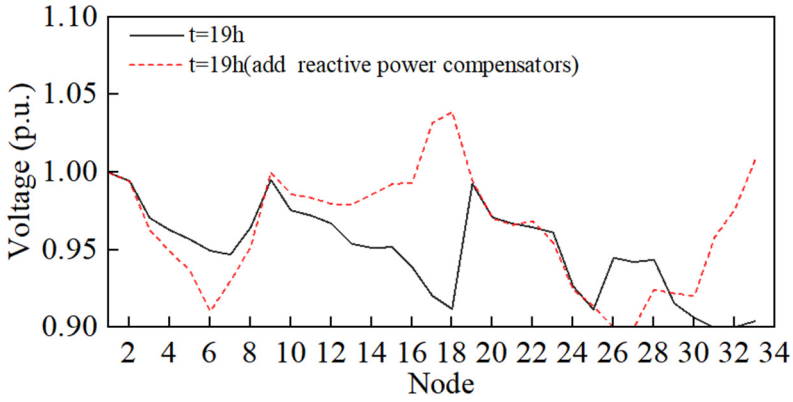


Figure 8. Voltage curves of t = 19 h.

As shown in Figure 8, at t = 19 h, without considering reactive power compensation devices, the voltage at the grid node where the energy storage is located is at the edge of the safe and feasible operating range, and the energy storage cannot be charged at a low

price at this time; when considering reactive power compensation devices, they provide voltage support to the power grid to address voltage safety challenges, and the feasible range of safe operation of the power grid no longer limits the charging and discharging behavior of energy storage.

In Figure 9, with the integration of reactive power compensators, the winning bid quantity of S1 in the energy market changes significantly. At this point, the energy storage can roughly follow a strategy of charging during low-price periods and discharging during high-price periods. This improvement is because when dispatching active power, the energy storage system must consider network security and topology constraints. When the voltage is at a critical level, reactive power compensators can quickly provide reactive power to alter the distribution of power flow around the node, impacting the voltage of the node and its surrounding nodes. This, in turn, influences the active power output of the energy storage.

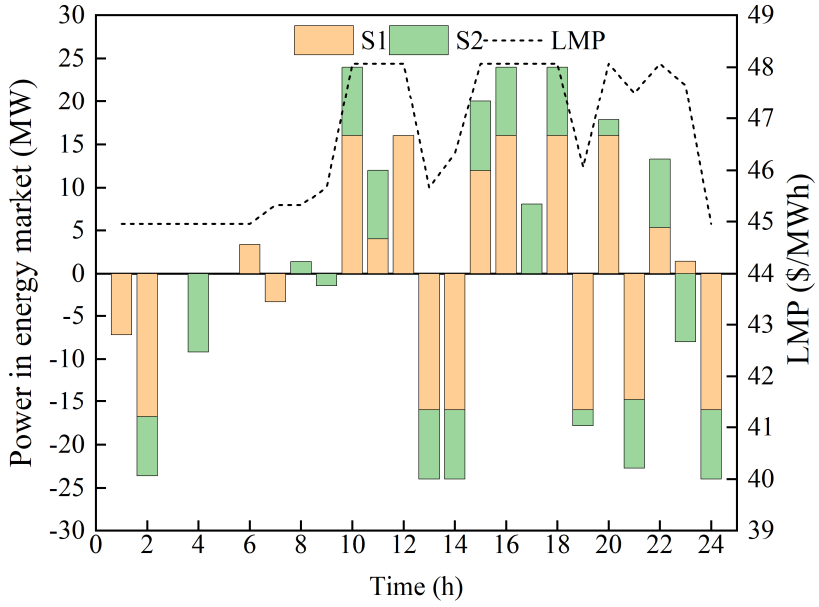


Figure 9. Bidding in the electric energy market of case 2.

In a word, when the energy storage equipped with reactive power compensators participates in the grid dispatching operation, the reactive power compensator can provide dynamic voltage support by injecting or absorbing reactive power so as to maintain the voltage level within a safe operating range. At the same time, energy storage can provide active power support to the grid. The combination of the two enables more efficient grid voltage regulation, stabilizes the grid in the event of fluctuations, reduces the risk of voltage overruns, and increases the resilience of the grid, thus ensuring that the grid remains stable even in the event of high reactive power demand or supply interruptions.

Table 3 presents the profits of energy storage in the energy market and ancillary services market before and after the integration of reactive power compensators. The revenue components in the market are settled based on the respective clearing prices and winning bid quantities.

Table 3. Profits of energy storage participation in joint market.

Case	Profit of Energy Storage in the Market (USD)
Case 1	4195.45
Case 2	4341.10

With the addition of reactive power compensators, it will be found that the benefits of energy storage have increased to a certain extent. In this case study, compared to the situation without a reactive power compensator, the revenue of energy storage with a reactive power compensator increased by 3.47%. This improvement is owing to the fact that the energy storage is initially operating at the edge of the feasible region of the power grid, which restricts its ability to perform normal "arbitrage" activities. The integration of reactive power compensators alters the power flow distribution around the energy storage. When the power output or input of the energy storage is constrained by network topology limitations, the reactive power compensators can provide or absorb reactive power to expand the feasible region for safe grid operation, thereby improving voltage regulation and increasing the revenue of energy storage.

5.2. The Influence of Distribution Grid Security on Energy Storage

Figure 10 reflects the winning bid of energy storage in the joint market before considering the network security topology constraints. It will be found that at t = 13–14 h, the clearing price of the market is relatively low, and energy storage purchases electricity from the market and stores the amount of electricity at that time. At t = 16–18 h, the clearing price of the market is relatively high, and energy storage sells electricity to the market to earn profits. Overall, in this situation, energy storage can effectively utilize its energy "transfer" characteristics in the energy market, bringing economic profits to itself.

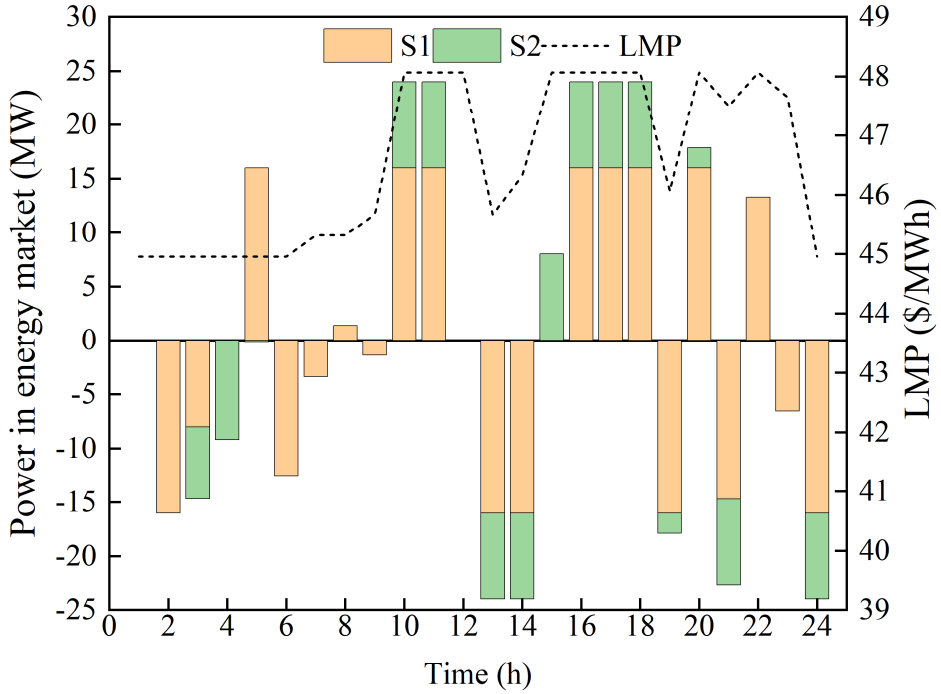


Figure 10. Bidding in the electric energy market without considering network security constraints.

As shown in Figure 11, in this case, if all the winning bids are delivered, energy storage can earn USD 4341.10 in revenue by participating in the market, but at this point, the voltage of the entire distribution network system has reached 0.80 p.u. At the lowest level, the grid's voltage will be overrun. In this scenario, because the safety constraints of the distribution network cannot be met, the winning bid for energy storage cannot be fully delivered, which will face the market's assessment problems and cause economic losses.

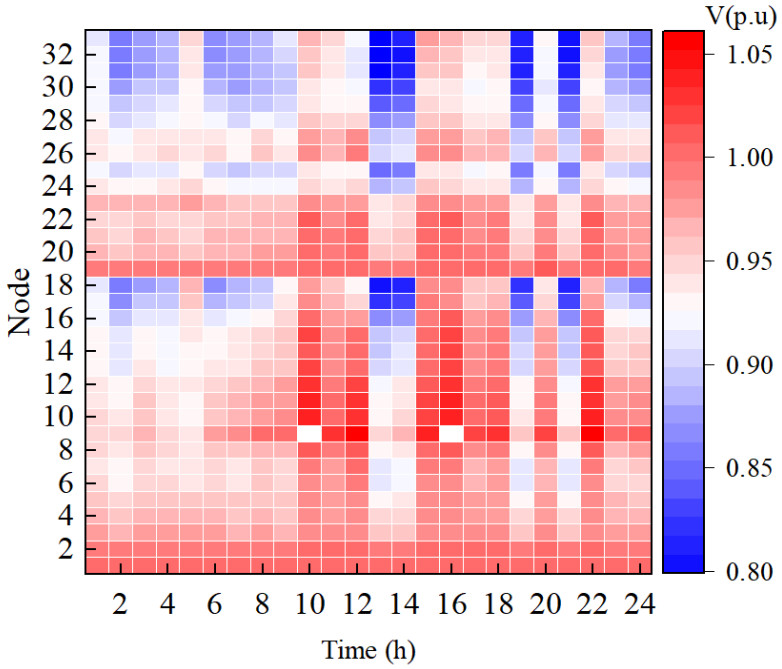


Figure 11. Voltage distribution of distribution network without considering network security constraints.

As shown in Figure 7, compared to Figure 10, it is evident that when considering network security topology, to avoid voltage limit violations, the charging and discharging power of the energy storage is restricted at certain times. This results in a decrease in the economic benefits that energy storage could achieve by leveraging its energy "transfer" capabilities. As illustrated in Figure 12 and Table 4, if the energy storage delivers according to its winning bid quantity, the revenue from participating in the market becomes USD 4195.45. The voltage of the distribution network has not exceeded the limit and is within a safe operating range upon inspection. At this point, the energy storage realizes the secure operation of the distribution grid by sacrificing some of its revenues.

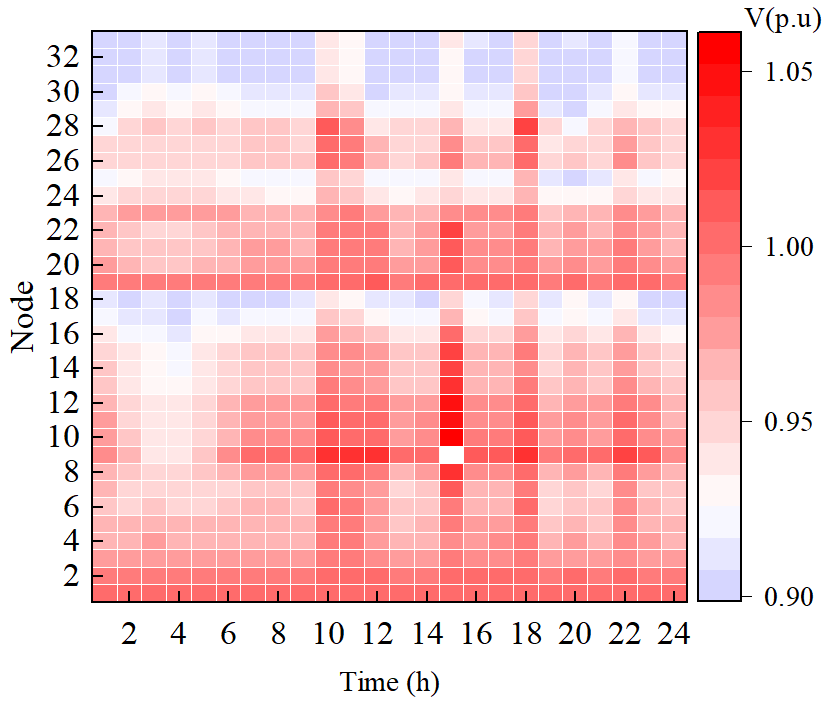


Figure 12. Voltage distribution of distribution network considering network security constraints.

Table 4. Profits of energy storage participation in the market.

Case	Profit of Energy Storage in the Market (USD)
Considering network security constraints	4195.45
No considering network security constraints	4341.10

Consequently, on the occasion that storage participates in the market bidding, it is essential for the energy storage to consider the network security topology constraints of the distribution network, and based on the secure operation of the network, it is meaningful for energy storage to maximize its revenue by optimizing its bidding strategy.

5.3. The Impact of the Location and the Capacity of Energy Storage with Reactive Power Compensators

Scenario 1: Energy storages with reactive power compensators are located at node 18 and node 26, respectively.

Scenario 2: Energy storages with reactive power compensators are located at node 18 and node 31, respectively.

Scenario 3: Energy storages with reactive power compensators are located at node 15 and node 21, respectively.

As shown in Table 5, it will be noticeable that some variation exists in the benefits of energy storage with reactive power compensators at different nodes in the distribution network. When the energy storage takes network topology security into account, its bidding results are influenced by these constraints. When operating at the edge of the feasible region, the energy storage with the reactive power compensator can only provide reactive power support by sacrificing its output in the active power market. This also indicates that in areas with high reactive loads or older neighborhoods with severe line degradation, increased reactive power demand and higher reactive power losses can lead to significant voltage drops. This situation may cause the node voltage to approach the edge of the feasible region for safe grid operation. Therefore, when considering the deployment of energy storage in such locations, it is crucial to consider adding the reactive power compensator to meet the grid's security requirements, ensuring both the secure operation of the grid and the maximization of energy storage revenue.

Table 5. Profits of energy storage with reactive power compensators in different locations.

Scenario	Profit of Energy Storage in the Market (USD)
Scenario 1	4341.10
Scenario 2	4304.98
Scenario 3	4330.40

As illustrated in Figure 13, the results show the changes in revenue for the energy storage when only S1 or S2 is equipped with the reactive power compensator. It is evident that with the continuous increase in reactive power capacity allocated to the energy storage, the incremental effect of the reactive power compensator on energy storage revenue does not persist. When the capacity of the reactive power compensator reaches a certain level, the revenue of the energy storage in the market no longer changes, indicating the presence of a benefit saturation effect. This demonstrates that simply increasing the capacity of the reactive power compensator is not always beneficial; there is a saturation point beyond which additional capacity does not enhance energy storage revenue.

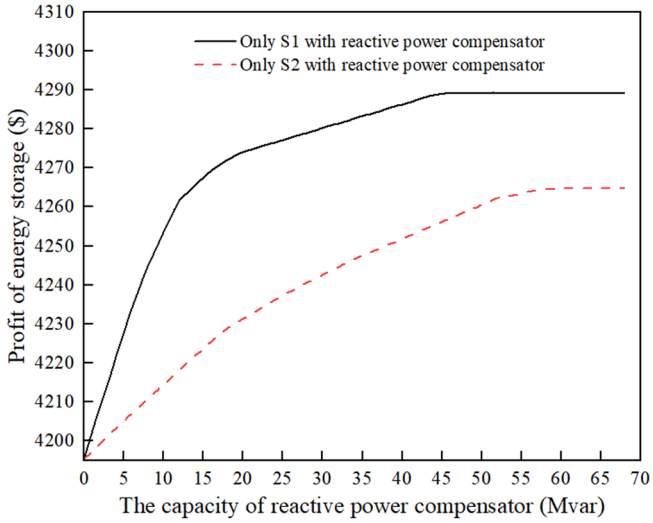


Figure 13. Energy storage benefits with reactive power compensator capacity.

6. Conclusions

This article is based on a bi-level model to consider the effect of reactive power compensators on energy storage bidding. The proposed model can fully consider the effect of reactive power distribution on active power dispatch while considering the secure and economic operation of the distribution network. It was shown that reactive power compensators have a certain incremental effect on the benefits of energy storage participation in the market, but this incremental effect does not always exist. When the capacity of reactive power compensators increases to a certain extent, the income from energy storage no longer increases, and there is a saturation effect. By configuring the reactive power compensator for energy storage, the market revenue of energy storage participation has increased by 3.47%. In general, this work shows that the reactive power compensator has an incremental impact on energy storage revenue and verifies that the operation mode of energy storage with reactive power compensators is of great application value in the power grid.

With the continuous development of the electricity market, the active power market has gradually improved, but the pricing mechanism and market clearing method of reactive power in the reactive power market have not been solved. Therefore, the joint optimization of the active–reactive market will be a promising subject for future work.

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References

1. Lamp, S.; Samano, M. Large-Scale Battery Storage, Short-Term Market Outcomes, and Arbitrage. *Energy Econ.* **2022**, *107*, 105786. [CrossRef]
2. Zamani-Dehkordi, P.; Chitsaz, H.; Rakai, L.; Zareipour, H. A Price Signal Prediction Method for Energy Arbitrage Scheduling of Energy Storage Systems. *Int. J. Electr. Power Energy Syst.* **2020**, *122*, 106122. [CrossRef]
3. Wang, Y.; Dvorkin, Y.; Fernandez-Blanco, R.; Xu, B.; Qiu, T.; Kirschen, D.S. Look-Ahead Bidding Strategy for Energy Storage. *IEEE Trans. Sustain. Energy* **2017**, *8*, 1106–1117. [CrossRef]
4. Zafirakis, D.; Chalvatzis, K.J.; Baiocchi, G.; Daskalakis, G. The Value of Arbitrage for Energy Storage: Evidence from European Electricity Markets. *Appl. Energy* **2016**, *184*, 971–986. [CrossRef]
5. Hao, L.; Cai, Y.; Wang, Z.; Wang, J.; Lv, X. Quantity-price bidding strategy of energy storage in electric energy market considering operation and planning benefit compensation. *Electr. Power Autom. Equip.* **2024**, *44*, 36–43. [CrossRef]
6. Pusceddu, E.; Zakeri, B.; Castagneto Gissey, G. Synergies between Energy Arbitrage and Fast Frequency Response for Battery Energy Storage Systems. *Appl. Energy* **2021**, *283*, 116274. [CrossRef]
7. Dunn, B.; Kamath, H.; Tarascon, J.-M. Electrical Energy Storage for the Grid: A Battery of Choices. *Science* **2011**, *334*, 928–935. [CrossRef] [PubMed]
8. Cha, S.-H.; Kwak, S.-H.; Ko, W. A Robust Optimization Model of Aggregated Resources Considering Serving Ratio for Providing Reserve Power in the Joint Electricity Market. *Energies* **2023**, *16*, 7061. [CrossRef]
9. Yu, P.; Zhu, J.; Liang, J.; Chen, H.; Xiong, X. Construction Method of Ancillary Emergency Backup Service Based on Battery Energy Storage System. *Int. J. Electr. Power Energy Syst.* **2023**, *147*, 108881. [CrossRef]
10. Ma, M.; Huang, H.; Song, X.; Peña-Mora, F.; Zhang, Z.; Chen, J. Optimal Sizing and Operations of Shared Energy Storage Systems in Distribution Networks: A Bi-Level Programming Approach. *Appl. Energy* **2022**, *307*, 118170. [CrossRef]
11. Yong, X.; Wu, Y.; Zhou, J.; Tao, Y.; Chen, W. Prospects and Barriers Analysis Framework for the Development of Energy Storage Sharing. *Sustain. Cities Soc.* **2023**, *89*, 104368. [CrossRef]
12. Jia, Q.; Li, Y.; Yan, Z.; Chen, S. Reactive Power Market Design for Distribution Networks with High Photovoltaic Penetration. *IEEE Trans. Smart Grid* **2023**, *14*, 1642–1651. [CrossRef]
13. Jiang, M.; Guo, Q.; Sun, H.; Ge, H. Leverage Reactive Power Ancillary Service under High Penetration of Renewable Energies: An Incentive-Compatible Obligation-Based Market Mechanism. *IEEE Trans. Power Syst.* **2022**, *37*, 2919–2933. [CrossRef]
14. Meng, Y.; Qiu, J.; Zhang, C.; Lei, G.; Zhu, J. A Holistic P2P Market for Active and Reactive Energy Trading in VPPs Considering Both Financial Benefits and Network Constraints. *Appl. Energy* **2024**, *356*, 122396. [CrossRef]
15. Ebrahimi, M.; Ebrahimi, M.; Shafie-khah, M.; Laaksonen, H. EV-Observing Distribution System Management Considering Strategic VPPs and Active & Reactive Power Markets. *Appl. Energy* **2024**, *364*, 123152. [CrossRef]
16. Jiang, T.; Dong, X.; Zhang, R.; Li, X. Strategic Active and Reactive Power Scheduling of Integrated Community Energy Systems in Day-Ahead Distribution Electricity Market. *Appl. Energy* **2023**, *336*, 120558. [CrossRef]
17. Ding, H.; Pinson, P.; Hu, Z.; Song, Y. Integrated Bidding and Operating Strategies for Wind-Storage Systems. *IEEE Trans. Sustain. Energy* **2016**, *7*, 163–172. [CrossRef]
18. Tang, Z.; Liu, Y.; Wu, L.; Liu, J.; Gao, H. Reserve Model of Energy Storage in Day-Ahead Joint Energy and Reserve Markets: A Stochastic UC Solution. *IEEE Trans. Smart Grid* **2021**, *12*, 372–382. [CrossRef]
19. McPherson, M.; McBennett, B.; Sigler, D.; Denholm, P. Impacts of Storage Dispatch on Revenue in Electricity Markets. *J. Energy Storage* **2020**, *31*, 101573. [CrossRef]
20. Krishnamurthy, D.; Uckun, C.; Zhou, Z.; Thimmapuram, P.R.; Botterud, A. Energy Storage Arbitrage under Day-Ahead and Real-Time Price Uncertainty. *IEEE Trans. Power Syst.* **2018**, *33*, 84–93. [CrossRef]
21. Ikechi Emmanuel, M.; Denholm, P. A Market Feedback Framework for Improved Estimates of the Arbitrage Value of Energy Storage Using Price-Taker Models. *Appl. Energy* **2022**, *310*, 118250. [CrossRef]
22. Wu, D.; Qi, T.; Wei, W.; Liu, J.; Chen, L.; Mei, S. An Efficient Decomposition Method for Bilevel Energy Storage Arbitrage Problem. *CSEE J. Power Energy Syst.* **2022**, *8*, 652–658. [CrossRef]
23. Barbry, A.; Anjos, M.F.; Delage, E.; Schell, K.R. Robust Self-Scheduling of a Price-Maker Energy Storage Facility in the New York Electricity Market. *Energy Econ.* **2019**, *78*, 629–646. [CrossRef]
24. Kardakos, E.G.; Simoglou, C.K.; Bakirtzis, A.G. Optimal Offering Strategy of a Virtual Power Plant: A Stochastic Bi-Level Approach. *IEEE Trans. Smart Grid* **2015**, *7*, 794–806. [CrossRef]
25. Tómasson, E.; Hesamzadeh, M.R.; Wolak, F.A. Optimal Offer-Bid Strategy of an Energy Storage Portfolio: A Linear Quasi-Relaxation Approach. *Appl. Energy* **2020**, *260*, 114251. [CrossRef]
26. Zhang, C.; Wang, Q.; Wang, J.; Korpås, M.; Pinson, P.; Østergaard, J.; Khodayar, M.E. Trading Strategies for Distribution Company with Stochastic Distributed Energy Resources. *Appl. Energy* **2016**, *177*, 625–635. [CrossRef]
27. Yuan, H.; Li, F.; Wei, Y.; Zhu, J. Novel Linearized Power Flow and Linearized OPF Models for Active Distribution Networks with Application in Distribution LMP. *IEEE Trans. Smart Grid* **2018**, *9*, 438–448. [CrossRef]

28. Yi, Z.; Xu, Y.; Wang, H.; Sang, L. Coordinated Operation Strategy for a Virtual Power Plant with Multiple DER Aggregators. *IEEE Trans. Sustain. Energy* **2021**, *12*, 2445–2458. [CrossRef]
29. Shandong Energy Regulatory Office, Shandong Provincial Development and Reform Commission, Shandong Provincial Energy Bureau Soliciting the "Shandong Province Electricity Spot Market Trading Rules" and "Shandong Province Electricity Medium and Long term Trading Rules", "Shandong Province Electricity Retail Market Trading Rules" [EB/OL]. 2020[2020-07-31]. Available online: https://sdb.nea.gov.cn/dtyw/tzgg/202309/t20230919_110428.html (accessed on 31 July 2020).
30. Ma, H.; Chen, Y.; Chen, Y.; Liu, W.; Lin, S.; Zhang, X. Mechanism design of southern China (starting from Guangdong Province) electric spot market. *South. Power Syst. Technol.* **2018**, *12*, 42–48. [CrossRef]
31. Xiao, Y.; Zhang, L.; Zhang, X.; Liu, Q. The coordinated market clearing mechanism for spot electric energy and regulating ancillary service incorporating independent energy storage resources. *Proc. CSEE* **2020**, *40* (Suppl. S1), 167–180. [CrossRef]
32. Mandić, M.; Sutlović, E.; Modrić, T. A General Model of Optimal Energy Storage Operation in the Market Conditions. *Electr. Power Syst. Res.* **2022**, *209*, 107957. [CrossRef]
33. Zarnikau, J.; Tsai, C.H.; Woo, C.K. Determinants of the Wholesale Prices of Energy and Ancillary Services in the U.S. Midcontinent Electricity Market. *Energy* **2020**, *195*, 117051. [CrossRef]
34. Wang, Y.; Zheng, Y.; Yang, Q. Optimal Energy Management of Integrated Energy Systems for Strategic Participation in Competitive Electricity Markets. *Energy* **2023**, *278*, 127883. [CrossRef]
35. Liang, Z.; Chung, C.Y.; Zhang, W.; Wang, Q.; Lin, W.; Wang, C. Enabling High-Efficiency Economic Dispatch of Hybrid AC/DC Networked Microgrids: Steady-State Convex Bi-Directional Converter Models. *IEEE Trans. Smart Grid*, 2024; *Early Access*. [CrossRef]

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