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A Distribution Network Planning Method Considering the Distributed Energy Resource Flexibility of Virtual Power Plants

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Abstract: To solve the overload problem caused by the high proportion of renewable energy into the power system, it is particularly important to find a suitable distribution network planning scheme. Existing studies have effectively reduced the planning cost by incorporating virtual power plants into the distribution planning process, but there is no quantitative analysis of the flexible resources inside the virtual power plant. At the same time, the traditional planning process does not pay much attention to the acquisition of photovoltaic and load data. Therefore, in this paper, we propose a distribution network planning method considering the flexibility of distributed energy resources in virtual power plants. Firstly, taking the distribution network planning including the virtual power plant as the research object, the flexibility of the distributed energy resource of the virtual power plant was quantified. Then, in order to achieve the goal of minimizing the operating cost of system planning, a distribution network planning model considering the flexibility of distributed energy resources in the virtual power plant is established. In this model, the impact of virtual power plants flexibility on the distribution network planning process is mainly considered. Secondly, this paper uses the improved k-means clustering algorithm to obtain the typical data of PV and load. The algorithm effectively overcomes the impact of PV and load output fluctuations on the planning process. Finally, the simulation results show that the proposed planning model can effectively reduce the operation cost of system planning by using distributed energy storage system and distributed energy resource flexibility. At the same time, the PV absorption rate of the PV power station inside the distribution network is improved.

Keywords: virtual power plant; distributed energy resource; distribution network planning; distributed energy storage system; flexibility quantization; improved k-means clustering algorithm

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1. Introduction

In the context of the global promotion of carbon emission reduction, the proportion of renewable energy such as photovoltaic (PV) in the power system continues to increase. However, the ensuing problem is that the uncertainty of renewable energy output such as photovoltaic will endanger the safety and stability of distribution network operation [1]. With the rapid development of power systems, the level of demand side load is also increasing. Demand-side resources under the new power system will become grid-side friendly and interactive resources, including electric vehicles (EVs), HVAC systems, etc. Due to the wide distribution of these resources, virtual power plant technology should be used to aggregate them to adjust the power load resources on the demand side, thereby improving the flexibility of the power grid [2].

In the existing research on distribution network planning, it is mainly to achieve the optimization objectives of reducing planning costs and peak load reduction. Among the existing methods to reduce the cost of the planning process and achieve peak filling, the most effective way is to increase the interaction between the distribution network and the demand side resources of the virtual power plant. Therefore, the distribution network planning process is closely related to the output characteristics of the source side and the load forecasting characteristics of the load side [3]. Therefore, the fluctuation of PV output and the participation of flexible resources on the demand side will affect the final planning results. Therefore, in order to reduce the planning cost, the existing research often includes the photovoltaic and distributed energy storage resources in the virtual power plant in the distribution network planning process.

At present, there are some literatures on flexible resources in virtual power plants. In order to characterize the flexibility of resources such as air conditioners and electric vehicles in virtual power plants, the authors in [4] established corresponding virtual battery models to achieve this goal. In [5], the membership matrix of flexible resources in each virtual power plant is obtained by cloud model method, and the subjective and objective weights are combined with the membership matrix to evaluate the level of flexible resources. The authors in [6] achieve joint optimization of their participation in power and reserve markets by evaluating the power availability zone of flexible resources within a virtual power plant. In [7], the authors proposed a method to characterize the flexibility of virtual power plants using flexible radar charts. In order to accurately evaluate the power generation characteristics of distributed generation resources in virtual power plants, the authors in [8] puts forward the corresponding evaluation criteria. In order to reduce system congestion, the authors in [9] considers the flexibility of distributed energy resource in virtual power plants and establishes a flexible trading market centered on the distribution network.

In view of the participation of virtual power plants and other flexible resources in the distribution network planning process, relevant studies have been carried out in the literature. In order to realize distribution network planning including distributed energy storage and distributed generation, the authors in [10,11] proposes a multi-objective coordinated planning model that comprehensively considers multiple factors. The authors proposed a multi-stage joint distribution network planning strategy in [12] to address the placement of EV charging stations and energy storage in the system. The authors in [13,14] in order to solve the problem of load fluctuation in the planning process, a distribution network planning method considering new load and distributed generation access is proposed. In [15,16], the authors all took island microgrid planning as the research object and effectively reduced the planning cost by introducing hydrogen storage systems. Based on the above studies, the authors in [17–20] focused on the safety and stability of the operation during the planning process of the distribution network including wind power and electric vehicles. In [21,22], the author integrated PV, energy storage and wind power and established a distributed energy management system. Then, the energy management system is integrated into the distribution network planning process to effectively improve the economy of the planning process. In order to achieve the goal of improving the economy of the planning process, the authors incorporated distributed energy into the planning process in the form of demand response in [23]. By introducing distributed energy storage and photovoltaic power generation in the distribution network planning process, the planned low-carbon economy goal is achieved. In [24,25], the authors incorporated distributed generation and energy storage in virtual power plants into the distribution planning process, which effectively reduced its planning cost. In [26], by integrating the flexibility of distributed energy into the planning process of urban distribution network, the author effectively reduces the cost of line expansion in the planning process by using load flexibility and conventional reinforcement methods.

The above studies included the virtual power plant with distributed energy resources into the distribution network planning, but did not quantitatively analyze the internal flexible resources of the virtual power plant. At the same time, it does not focus on

the impact of PV and load output fluctuations on the distribution network planning results. Therefore, this paper proposes a distribution network planning method that considers the distributed energy resource flexibility of virtual power plants. Compared with [10,11,15,16,23], the proposed model considers the fluctuation of PV and load output into the planning process. Furthermore, compared with [17–22], this paper adopts an improved k-means clustering algorithm to deal with the fluctuation of PV and load output. Compared with [12–14,24–26], the proposed model quantifies the flexibility of the demand side resources of the virtual power plant in the planning process of the distribution network. The main contributions of this paper are as follows.

(1) In the distribution network planning process, the improved k-means clustering algorithm is used for the fluctuation of PV and load output.
(2) The distributed energy resource flexibility model of virtual power plant is established to quantify the flexibility of demand side resources in virtual power plant during the planning process.
(3) The proposed programming model is converted into a typical mixed integer linear programming model by a second-order cone optimization technique. The improved IEEE RTS-24 node system is used to verify the superiority of the proposed programming model.

The remainder of this article consists of the following. Section 2 introduces the distribution network planning framework proposed in this paper. Section 3 discusses in detail the distributed energy resource flexibility model for virtual power plants with EVs. Section 4 introduces the programming model proposed in this paper, and gives the method of solving the model. In Section 5, the details of the example simulation are introduced and discussed. Finally, the conclusion is given in Section 6.

2. Distribution Network Planning Framework

The load in the power system always increases with the increase of the distribution network planning year, so it is necessary to invest in new lines or expand the original lines to maintain the stable operation of the system. Due to the increasing proportion of renewable energy access such as photovoltaic, distribution network planning also needs to consider many factors.

In order to solve the problems mentioned above, this paper puts forward a set of suitable distribution network planning schemes. Firstly, the paper brings virtual power plant flexibility resources into the distribution network planning process. Then, considering the investment cost of line expansion, the flexibility compensation cost of virtual power station, the investment cost of the energy storage system and the abandonment cost of the photovoltaic power station, the corresponding distribution network planning model is established. Finally, by solving the model, a distribution network planning scheme is obtained.

Virtual power plants as a new technology, through information collection, control and communication technology, it can aggregate cross-region, multi-type controllable distributed resources, and can effectively play the flexibility and complementarity of distributed resources. At the same time, as a typical class of adjustable load, electric vehicles achieve a flexible balance in all aspects of operation, which brings corresponding economic benefits. By introducing electric vehicles into the system as an effective means of transferring peak load to the system, planning costs can be further reduced. Therefore, this paper mainly focuses on the virtual power plant with distributed energy resource such as EV. Although the existing studies on the flexibility resources of virtual power plant mainly focus on the operation aspect, some studies also take it into consideration in the planning process. There are two main reasons for this. On the one hand, electric vehicles can play a role in cutting peaks and filling valleys. On the other hand, in order to obtain a better planning scheme, the concept of operation is usually introduced in the planning process, the planning and operation are jointly optimized. At same time, in order to obtain better

planning schemes, operational concepts are usually introduced in the planning process to obtain the best investment and operation schemes.

In this paper, the flexibility modeling of EV in a virtual power plant is used to describe its up-and-down standby capacity. Then, under the relevant constraints, a certain load adjustment margin is set quantitatively according to the flexibility of electric vehicles. The total power supply capacity of the superior grid, PV and energy storage systems is insufficient during peak power load hours. At this time, price compensation incentives can be used to guide flexible power loads to reduce electricity consumption. When the power load is in the off-peak period, the system guides the flexible load to increase the power consumption due to the surplus of the total power supply.

In order to overcome the impact of PV output fluctuation on the planning process, an improved k-means clustering algorithm is used to obtain the PV output data of 96 h in a typical year. At the same time, considering the characteristics of energy storage, each PV plant is equipped with a corresponding energy storage system. Similar to the acquisition of typical PV data, a modified k-means clustering algorithm was used to obtain typical load data for 96 h from historical data. The process of using the improved k-means clustering algorithm is shown in Figure 1.

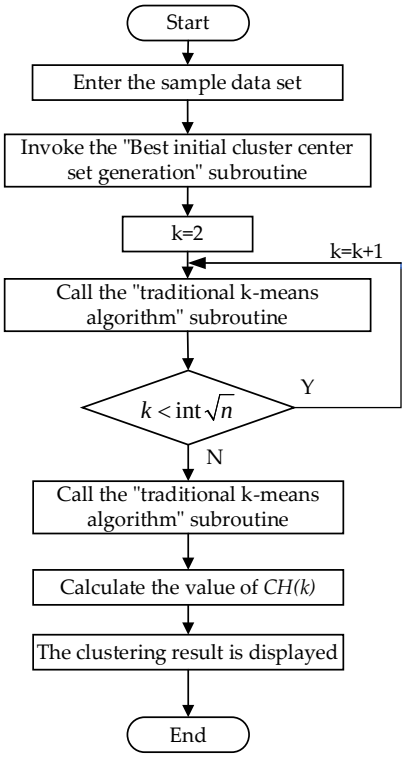

Figure 1. The process of using the improved k-means clustering algorithm.

In the flow chart, $CH(k)$ is the evaluation index of clustering effect of k-means algorithm. The value of $CH(k)$ reflects the effect of clustering, and the larger the value of $CH(k)$ indicates the better effect of clustering. The steps of the "Best initial cluster center set generation" subroutine are as follows.

Step1: Calculate the density parameter of each data and find the data S_n corresponding to the maximum value.

Step2: If S_n is unique, add S_n to the initial cluster center candidate set. If it corresponds to multiple sample data, the data with the smallest cohesion degree is selected according to the cohesion parameter and added to the initial cluster center candidate set.

Step3: Delete the data from the sample set with S_n as the center and d_{mean} (average distance of the sample) as the radius.

Step4: Repeat the process from Step1 to Step3 until an initial cluster center is found.

Finally, Figure 2 shows the proposed distribution network planning framework.

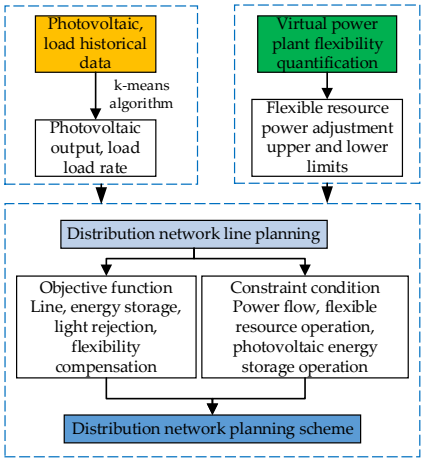

Figure 2. Planning framework.

3. Distributed Energy Resource Flexibility Model of Virtual Power Plant

In order to incorporate virtual power plants and EVs into the distribution network planning process as typical distributed energy sources, a quantitative model of cluster EVs flexibility based on EVs flexibility should be established first. Then, on the basis of this model, the charge and discharge optimization is carried out to improve the economy of Time-of-use electricity price (TOU) cluster electric vehicles [27]. The optimal charging and discharging power is obtained, and the standby capacity of EV cluster involved in centralized regulation is calculated as reference power. Secondly, the calculated results are used as the operating limits of the adjustable power of the flexible load of the virtual power plant in the planning process. Finally, by reducing the power consumption of flexible load during peak load hours, the flexible load during low power consumption periods can be effectively increased, the economy of planning can be improved, and the photovoltaic absorption rate can be improved.

When characterizing the reserve capacity of an electric vehicle, its charge-discharge limits must be observed. On the basis of analyzing the power feasible region of EV, the time axis is discretized, and the scheduling cycle of cluster EV is divided into T period, and the length of each period is Δt. Assume that the charge and discharge power in Δt remains unchanged, where the charge/discharge power of EV is as follows.

$$P_{i,t} = P_{i,t,c} u_{i,t,c} \eta_{i,c} - \frac{P_{i,t,d} u_{i,t,d}}{\eta_{i,d}} \tag{1}$$

$$0 \le P_{i,t,c} \le P_{c,\max} \tag{2}$$

$$0 \le P_{i,t,d} \le P_{d,\max} \tag{3}$$

$$u_{i,t,c} + u_{i,t,d} \le 1 \tag{4}$$

where, $P_{i,t,c}$, $P_{i,t,d}$ are respectively the power input and output of electric vehicles. $u_{i,t,c}$, $u_{i,t,d}$ represent the power input and output states of electric vehicles respectively, which are binary variables. $\eta_{i,c}$, $\eta_{i,d}$ are the power input and output efficiency of electric vehicles respectively. $P_{c,\max}$, $P_{d,\max}$, respectively represent the maximum power input and output power of electric vehicles. For this reason, the standby capacity of the EV will change with the change of the real-time power of the EV. Equation (1) represents the relationship between the real-time power of EV and its charging and discharging power. Equations (2) and (3)

indicate that the EV charging and discharging power cannot exceed the limit. Equation (4) indicates that EV charging and discharging cannot be carried out simultaneously.

When calculating the charging and discharging power of an EV, it is necessary to consider the limitations of its battery capacity, so the EV should be run as follows.

$$E \geq E_{\min} = \begin{cases} E_{base},\ t_{base} \leq t \leq t_d \\ E_{\exp} - P_{c,\max}(t_{\exp} - t),\ t > t_d \end{cases} \tag{5}$$

where, $E_{\min}$ is the minimum capacity of EV. E_{base} represents the minimum power level set by the user. $E_{\exp}$ represents the off-grid power of EV. t_{base} indicates the time for EV charging to the minimum charge. t_d is the off-network time of EV.

Under TOU, charge and discharge optimization is carried out with the goal of improving the operation economy of cluster electric vehicles, and the optimization objective function is as follows:

$$\max F_{evag} = \sum_{i \in N} \sum_{t \in T} f_{ev,i,t} \tag{6}$$

$$f_{ev,i,t} = f_{d,i,t} - f_{c,i,t} \tag{7}$$

$$f_{ev,i,t} \geq -P^0_{i,t,c} \pi_{c,t} \tag{8}$$

$$f_{c,i,t} = P_{i,t,c} \pi_{c,t} \tag{9}$$

$$f_{d,i,t} = P_{i,t.d} \pi_{d,t} \tag{10}$$

where, F_{evag} is the aggregate revenue of N EVs centrally controlled by the aggregator. $f_{ev,i,t}$ is the income of a single EV after centralized regulation $f_{d,i,t}$, $f_{c,i,t}$ respectively represent the discharge income and charging cost after EV participates in scheduling. $\pi_{d,t}$, $\pi_{c,t}$ are the discharge and charging prices of EV respectively. $P^0_{i,t,c}$ represents the real-time interactive power of electric vehicles that do not participate in centralized scheduling. Formula (8) ensures that after a single EV participates in centralized regulation, it has benefits compared with the previous individual charging. Equations (9) and (10) represent the charging cost and discharging benefit of a single EV, respectively.

The final optimized power of EV can be calculated by Formulas (1)–(11), and then the standby capacity of each EV can be obtained by considering the influence of power boundary and power boundary.

$$E_{i,t} = E_{i,0} + \gamma_{i,t} \sum_{t=1}^{T} P_{i,t} \tag{11}$$

$$P_{cu,i,t} = \gamma_{i,t} \max\left\{ \min(-P_{c,\max} + P_{i,t}, \frac{E_{i,t} - E_{\min,t+1}}{\Delta t} + P_{i,t}), 0 \right\} \tag{12}$$

$$P_{cd,i,t} = \gamma_{i,t} \max\left\{ \min(P_{d,\max} - P_{i,t}, \frac{E_{\max} - E_{i,t}}{\Delta t} - P_{i,t}), 0 \right\} \tag{13}$$

where, $E_{i,t}$ represent the real-time power of EV battery. $E_{i,0}$ is the initial charge of the EV battery. $\gamma_{i,t}$ indicates the online status of EV. $P_{cu,i,t}$, $P_{cd,i,t}$ are the upper and lower reserve capacities of EV respectively. $P_{d,\max} - P_{i,t}$, $-P_{c,\max} + P_{i,t}$ are the maximum increased charging and discharging power of EV respectively, that is, the power boundary. $(E_{i,t} - E_{\min,t+1})/\Delta t + P_{i,t}$ is the discharge space of EV, that is, the energy boundary. Equation (11) represents the relationship between EV real-time charge and power. For this purpose, the standby capacity of the electric vehicle can be obtained as shown in Figure 3.

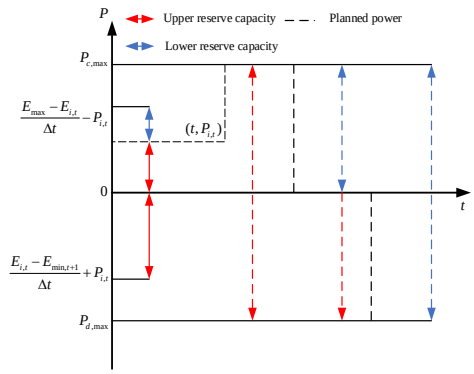

Figure 3. Electric vehicle backup capability.

In the subsequent planning model, the spare capacity of electric vehicles can be used as the adjustable power limit of the virtual power plant flexibility resources planned by the distribution network, as shown in the following equation:

$$P_t^{down,\max} = \sum_{i=1}^{N} P_{cu,i,t} \tag{14}$$

$$P_t^{up,\max} = \sum_{i=1}^{N} P_{cd,i,t} \tag{15}$$

where, $P_t^{down,\max}$, $P_t^{up,\max}$ represent the down and up boundaries of the flexibility resources of the virtual power plant respectively.

4. Distribution Network Planning Model

This section introduces the construction of distribution network planning model, taking into account the factors of peak loading and valley filling and new energy consumption [28]. In this model, all economic costs are converted to average annual investment at the time of planning. Firstly, by solving the model proposed in Section 3, the adjustable power upper and lower limits of 96 h in typical planning year of distribution network are obtained. Then, the flexibility of virtual power plant electric vehicles and distributed energy storage are utilized to reduce the investment cost of line expansion and the cost of light abandonment. Finally, the power balance constraint, power flow constraint, virtual power plant flexible operation constraint, photovoltaic operation constraint, main network exchange power constraint, energy storage operation constraint, voltage and current safety constraint and other related constraints are comprehensively considered for distribution network planning [29].

4.1. Objective Function

The objective function of distribution network planning model consists of four parts. It includes the flexibility compensation cost of virtual power station, the investment cost of energy storage system, the investment cost of distribution network line expansion and the abandonment cost of photovoltaic power station.

$$\min C = c_{line} + c_{dsr} + c_{ess} + c_{cur} \tag{16}$$

where, c_{line} represents the investment cost of distribution network line expansion. c_{dsr} is the flexibility compensation cost of virtual power station. c_{ess} represents the investment cost of energy storage system. c_{cur} is the abandonment cost of photovoltaic power station. Its specific expression forms are as follows.

4.1.1. The Investment Cost of Distribution Network Line Expansion

$$c_{line} = \frac{r(1+r)^n}{(1+r)^n - 1} \sum_{ij \in \theta_l} c_{ij} m_{ij} \tag{17}$$

where, r is the discount rate of line investment. n indicates the planned usage year. In this document, the value is 10. θ_l indicates the branch set to be built. c_{ij} represents the cost of building a single line. m_{ij} indicates the number of new lines.

4.1.2. The Flexibility Compensation Cost of Virtual Power Station

$$c_{dsr} = \sum_{v \in \delta_T} d_v \sum_{t=1}^{T} (c_t^{up} \sum_{j \in \delta_{up}} P_{t,v,j}^{up} + c_t^{down} \sum_{i \in \delta_{down}} P_{t,v,i}^{down}) \tag{18}$$

where, δ_T represents the set of typical days. δ_{up}, δ_{down} represent the set of nodes in the system where the load can be raised and lowered respectively. d_v indicates the number of days in a typical day. c_t^{up}, c_t^{down} respectively represent the unit compensation electricity price that can be raised and lowered in the system. $P_{t,v,j}^{up}$, $P_{t,v,i}^{down}$ indicate that the load capacity in the system can be increased and decreased respectively.

4.1.3. The Investment Cost of Energy Storage System

$$c_{ess} = (1 + r_{op} + r_{ma} + r_{sc}) r_{de} \sum_{i \in \delta_{ess}} (c_p P_{ess,i}^r + c_e E_{ess,i}^r) \tag{19}$$

where, c_p, c_e represent the unit power and capacity cost of the energy storage system respectively. r_{op}, r_{ma}, r_{sc}, r_{de} represent the conversion coefficients of the operation, maintenance, disposal and depreciation costs of the energy storage system respectively. δ_{ess} indicates the node set for configuring the energy storage system. $P_{ess,i}^r$, $E_{ess,i}^r$ are the rated power and capacity of the energy storage system respectively.

4.1.4. The Abandonment Cost of Photovoltaic Power Station

$$c_{cur} = \sum_{i \in \delta_{PV}} \sum_{v \in \delta_T} d_v \sum_{t=1}^{T} c_{PV} (P_{t,v,i}^{PV,\max} - P_{t,v,i}^{PV}) \tag{20}$$

where, δ_{PV} is the set of nodes configured with photovoltaic power stations. c_{PV} represents the unit cost of light abandonment of photovoltaic power stations. $P_{t,v,i}^{PV,\max}$, $P_{t,v,i}^{PV}$ represent the maximum power limit and actual output power of the photovoltaic power station respectively.

4.2. Constraint

4.2.1. Power Balance Constraint

$$P_{t,v}^{buy} + P_{t,v}^{PVess} - A^{new} P_{ij,t,v}^{new} - A^{old} P_{ij,t,v}^{old} = P_{t,v}^{up} + P_{t,v}^{load} - P_{t,v}^{down} \tag{21}$$

$$Q_{t,v}^{buy} + Q_{t,v}^{PVess} - A^{new} Q_{ij,t,v}^{new} - A^{old} Q_{ij,t,v}^{old} = Q_{t,v}^{load} \tag{22}$$

$$P_{t,v}^{PVess} = P_{t,v}^{PV} - P_{t,v}^{ess} \tag{23}$$

$$Q_{t,v}^{PVess} = Q_{t,v}^{PV} - Q_{t,v}^{ess} \tag{24}$$

where, $P_{t,v}^{buy}$, $Q_{t,v}^{buy}$ are the power interaction values of the distribution network and the upper power market, respectively. $P_{t,v}^{PVess}$, $Q_{t,v}^{PVess}$ are active power and reactive power of

optical storage combination respectively. $P_{ij,t,v}^{new}$, $Q_{ij,t,v}^{new}$ represent the real-time power of a new line on a typical day. $P_{ij,t,v}^{old}$, $Q_{ij,t,v}^{old}$ respectively represent the real-time power of the existing line on a typical day. A^{new}, A^{old} represent the node association matrix of the new and existing branches respectively. $P_{t,v}^{load}$, $Q_{t,v}^{load}$ are active and reactive power loads on typical days respectively. $P_{t,v}^{ess}$, $Q_{t,v}^{ess}$ respectively represent the real-time power output of the energy storage system. Equations (21) and (22) are the active and reactive power balance of the distribution network, respectively.

4.2.2. Power Flow Constraint of Distribution Network

$$\sum_{i \in r(j)} (P_{ij,t,v} - \frac{P_{ij,t,v}^2 + Q_{ij,t,v}^2}{U_{i,t,v}^2} r_{ij}) = P_{j,t,v} + \sum_{c \in s(j)} P_{jc,t,v} \tag{25}$$

$$\sum_{i \in r(j)} (Q_{ij,t,v} - \frac{P_{ij,t,v}^2 + Q_{ij,t,v}^2}{U_{i,t,v}^2} x_{ij}) = Q_{j,t,v} + \sum_{c \in s(j)} Q_{jc,t,v} \tag{26}$$

$$U_{i,t,v}^2 - U_{j,t,v}^2 = 2(r_{ij} P_{ij,t,v} + x_{ij} Q_{ij,t,v}) - I_{ij,t,v}^2 (r_{ij}^2 + x_{ij}^2) \tag{27}$$

where, r_{ij}, x_{ij} are the resistance and reactance of branch ij. $P_{ij,t,v}$, $Q_{ij,t,v}$ represent the real-time power of branch ij respectively. $P_{j,t,v}$, $Q_{j,t,v}$ represent the real-time injected power of node j respectively. $U_{i,t,v}$, $I_{ij.t,v}$ represent the voltage of node i and the current on branch ij, respectively. $r(j)$ represents the first node set with j as the tail node. $s(j)$ represents the set of tail nodes starting with j.

The above power flow constraints are strongly non-convex constraints, and their direct computation is complicated. Therefore, the second order conical convex optimization technique is used to transform the above constraints into linear constraints. The square of the line node voltage and branch current is defined as $U'_{i,t,v}$, $I'_{ij,t,v}$. Therefore, when the square of the branch current is a strictly increasing function of the objective function, and the node load is not set to a limit, there are as follows.

$$I'_{ij,t,v} \geq \frac{P_{ij,t,v}^2 + Q_{ij,t,v}^2}{U_{i,t,v}^2} \tag{28}$$

Therefore, the power flow constraint Formulas (25)–(27) of the distribution network can be converted into the following form after transformation.

$$\sum_{i \in r(j)} (P_{ij,t,v} - I'_{ij,t,v} r_{ij}) = P_{j,t,v} + \sum_{c \in s(j)} P_{jc,t,v} \tag{29}$$

$$\sum_{i \in r(j)} (Q_{ij,t,v} - I'_{ij,t,v} x_{ij}) = Q_{j,t,v} + \sum_{c \in s(j)} Q_{jc,t,v} \tag{30}$$

$$U'_{i,t,v} - U'_{j,t,v} = 2(r_{ij} P_{ij,t,v} + x_{ij} Q_{ij,t,v}) - I'_{ij,t,v} (r_{ij}^2 + x_{ij}^2) \tag{31}$$

$$\left\| \begin{array}{l} 2P_{ij,t,v} \\ 2Q_{ij,t,v} \\ I'_{ij,t,v} - U'_{i,t,v} \end{array} \right\|_2 \leq I'_{ij,t,v} + U'_{i,t,v} \tag{32}$$

4.2.3. Constraints on the Flexible Operation of Virtual POWER Plants

$$u_{t,v,i}^{down} + u_{t,v,i}^{up} \leq 1 \tag{33}$$

$$0 \leq P_{t,v,i}^{down} \leq P_{t,v,i}^{down,\max} u_{t,v,i}^{down} \tag{34}$$

$$0 \leq P_{t,v,i}^{up} \leq P_{t,v,i}^{up,\max} u_{t,v,i}^{up} \tag{35}$$

$$\sum_{t}^{t+T^{down,\max}} u_{t,v,i}^{down} \leq T^{down,\max} \tag{36}$$

$$\sum_{t}^{t+T^{up,\max}} u_{t,v,i}^{up} \leq T^{up,\max} \tag{37}$$

In the formula, $u_{t,v,i}^{down}$, $u_{t,v,i}^{up}$ represent the state of virtual power plant flexible load reduction and load increase respectively. $P_{t,v,i}^{down,\max}$, $P_{t,v,i}^{up,\max}$ represent the flexible load reduction and upward load boundary of a typical day virtual power plant respectively. $T^{down,\max}$, $T^{up,\max}$ represent the maximum continuous downward adjustment and upward adjustment time of virtual power plant flexibility load respectively.

4.2.4. Constraints on Photovoltaic Operation

$$0 \leq P_{t,v,i}^{PV} \leq P_{t,v,i}^{PV,\max} \tag{38}$$

$$0 \leq Q_{t,v,i}^{PV} \leq Q_{t,v,i}^{PV,\max} \tag{39}$$

where, $P_{t,v,i}^{PV,\max}$, $Q_{t,v,i}^{PV,\max}$ are the maximum power output of the photovoltaic power station.

4.2.5. Constraint on Switching Power of the Main Network

$$0 \leq P_{t,v}^{buy} \leq P^{buy,\max} \tag{40}$$

$$0 \leq Q_{t,v}^{buy} \leq Q^{buy,\max} \tag{41}$$

where, $P^{buy,\max}$, $Q^{buy,\max}$ are the maximum interaction power with the upper power market.

4.2.6. Energy Storage Operation Constraints

$$0 \leq P_{t,v}^{ess,d} \leq P_{t,v}^{ess,d,\max} \tag{42}$$

$$0 \leq P_{t,v}^{ess,c} \leq P_{t,v}^{ess,c,\max} \tag{43}$$

$$P_{t,v}^{ess} = P_{t,v}^{ess,c} \xi_c - \frac{P_{t,v}^{ess,d}}{\xi_d} \tag{44}$$

$$E^{ess,\min} \leq E_{t,v}^{ess} \leq E^{ess,\max} \tag{45}$$

$$E_{t,v}^{ess} + \sum_{\tau=1}^{t} \left[(\lambda_{\mathrm{ds}})^{t-\tau} P_{t,v}^{ess} \right] = E^{ess,0} \tag{46}$$

where, λ_{ds} is the power conversion coefficient of the energy storage. $P_{t,v}^{ess,d}$, $P_{t,v}^{ess,c}$ respectively represent the real-time power output and input of the energy storage. $P_{t,v}^{ess,d,\max}$, $P_{t,v}^{ess,c,\max}$ respectively represent the maximum power output and input of the energy storage. ξ_d, ξ_c respectively represent the maximum power output and input efficiency of the energy storage. $E_{t,v}^{ess}$, $E^{ess,0}$ represent the storage real-time energy and initial energy respectively. $E^{ess,\min}$, $E^{ess,\max}$ respectively represent the energy storage capacity limits.

4.2.7. Voltage and Current Safety Constraints

$$0 \le U_{i,t,v}' \le U_{i,t,v}^{',\max} \tag{47}$$

$$0 \le I_{i,t,v}' \le I_{i,t,v}^{',\max} \tag{48}$$

where, $U_{i,t,v}^{',\max}$, $I_{i,t,v}^{',\max}$ are the maximum values of the square of node voltage and the square of branch current, respectively.

In the aspect of model solving, the proposed programming model is transformed into a directly solvable mixed integer linear programming model by using second-order cone optimization technique. This paper intends to use YALMIP on MATLAB platform for mathematical modeling of the model, and call CPLEX solver for solving.

5. Simulation Results and Analysis

5.1. Model Building

In this paper, the superiority of the proposed programming model is verified by simulation on IEEE RTS-24 node system. The relevant data of this node are referred to [30]. Meanwhile, the 96-h photovoltaic output and conventional load data are shown in Figures 4 and 5.

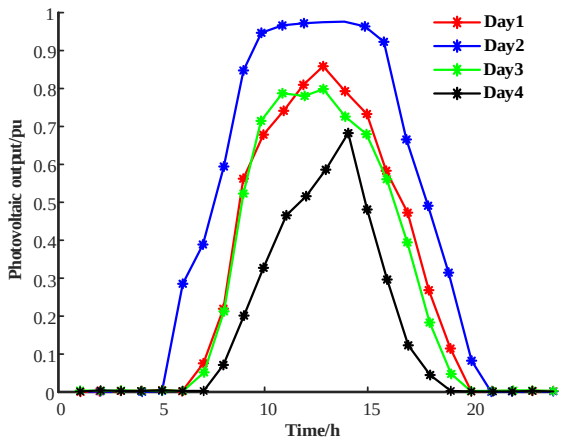

Figure 4. PV output in 96 h.

By solving the model presented in Section 3, the time series load power data and adjustable power range of the EV flexible load in the virtual power plant can be obtained. In this example, the charge and discharge power limit is 3 kW, the battery capacity ranges from 0.1 to 1 kWh during operation, and the battery capacity is set to 30 kWh. The calculated sequential load power data of 10,000 electric vehicles for 96 h and the adjustable power range up and down are shown in Figure 6. Among them, the quantified adjustable power range of electric vehicles will be used as the upward and downward load boundary in planning model.

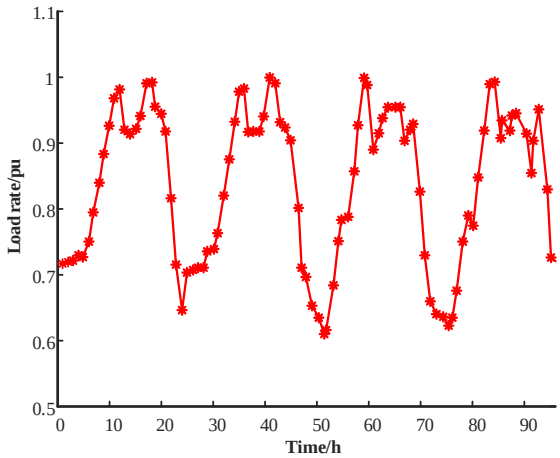

Figure 5. 96 h load rate.

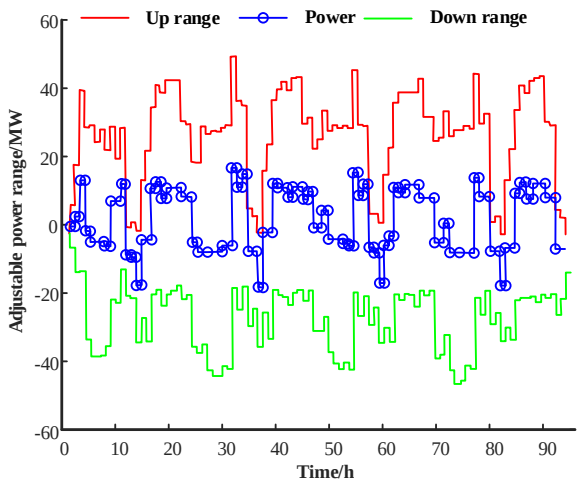

Figure 6. The sequential load power of 10,000 electric vehicles for 96 h and its adjustable power range up and down.

In the example setting, the 60 MW PV power station is connected on nodes 3, 8, 9, 10, 14 and 19 respectively, and the 130 MW PV power station is connected on nodes 7, 21, 22 and 23 respectively. In addition, each photovoltaic power station is equipped with an energy storage system, and its related parameters are shown in Table 1. At the same time, 10,000 electric vehicles are set up at nodes 3, 6, 9, 13, 15 and 18 as demand-side flexibility resources. The time-sharing compensation price of flexible load in virtual power plant is shown in Table 2.

Table 1. Related parameters of energy storage system.

Parameters	Value	Parameters	Value
r_{op}	0.02	r_{sc}	0.01
r_{de}	0.05	c_p (yuan/kW)	300
r_{ma}	0.02	c_e (yuan/kW)	3500

Table 2. Time-of-use compensation price.

Time	09:00–14:00 18:00–22:00	00:00–07:00 22:00–24:00	07:00–09:00 14:00–18:00
c_{down}	0.30	0.10	0.25
c_{up}	0.15	0.35	0.25

Finally, a 5-year distribution network planning work is carried out based on the above example setting, and the planning results are reflected in the economic cost of line expansion and planning.

5.2. Analysis of Result of Example Planning

In order to reflect the improvement of virtual battery flexibility resources on distribution network planning results and new energy consumption, this paper compares the planning results by setting two different cases.

Case 1. The flexibility of the virtual power plant flexibility resources is quantified before being incorporated into the distribution network planning process.

Case 2. The VPP flexibility resources are directly incorporated into the distribution network planning process.

5.2.1. Result Analysis of Line Expansion

In the actual planning process, the initial route scheme of this year is the optimal solution of the previous year's planning scheme. The optimization results of five-year distribution network line planning under the two cases are shown in Tables 3 and 4 respectively, where "6–10(1)" indicates that a line needs to be expanded between nodes 6 and 10 in the planning year.

Table 3. Results of planned line expansion for distribution network in Case 1.

Year	Line Expansion
1	6–10(1), 7–8(2), 13–14(1)
2	1–5(1), 7–8(1)
3	20–22(1)
4	3–22(1), 6–8(1), 10–12(1)
5	2–5(1), 9–11(1), 14–22(1)

Table 4. Results of planned line expansion for distribution network in Case 2.

Year	Line Expansion
1	6–10(1), 7–8(2), 10–11(1), 13–14(1)
2	1–5(1), 7–8(1), 10–12(1)
3	3–22(1), 20–22(1), 10–12(1)
4	3–22(1), 6–8(1), 10–12(1), 10–11(1), 13–14(1)
5	2–5(1), 7–8(1), 15–16(1), 15–23(1), 16–18(1)

As can be seen from Tables 3 and 4, compared with case 2, by adding flexibility resources to distribution network planning in case 1. It can be seen that the required line expansion in each planning year is significantly reduced, effectively reducing the overall planning cost.

5.2.2. Economic Analysis of Planning Results

In order to verify the advantages of the proposed planning model in improving the planning economy, the total planning costs of the two schemes were compared, as shown in Figure 7. The data column on the left of each planning year is the planning result of Case 1, and the data column on the right is the planning result of Case 2. In order to compare the difference between the individual costs of the two cases in detail, the comparison of line investment costs of the two cases is shown in Figure 8. The comparison of the abandoned light cost of photovoltaic power stations in the two cases is shown in Figure 9.

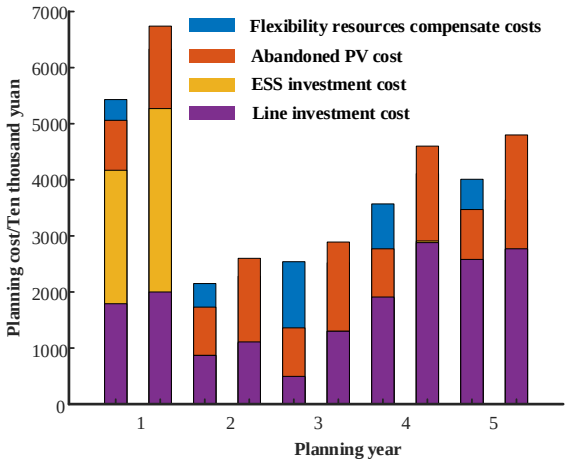

Figure 7. Distribution network planning cost comparison.

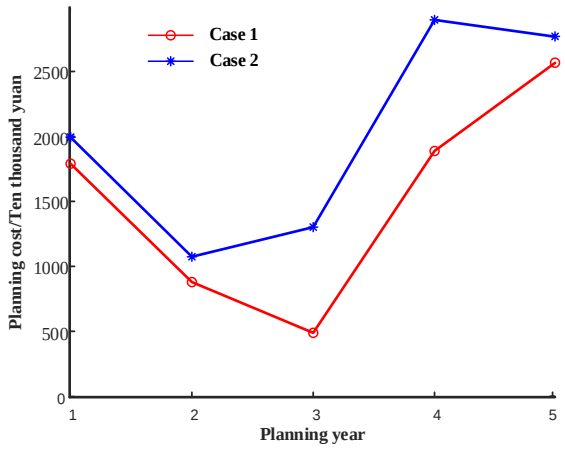

Figure 8. Line investment cost comparison.

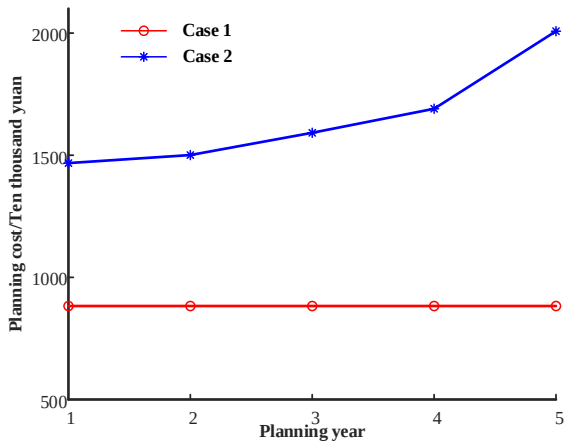

Figure 9. Comparison of abandoned light cost of photovoltaic power station.

As can be seen from Figure 7, by adding flexibility resources to distribution network planning in case 1, the annual total planning cost is lower than that in case 2. Therefore, the planning strategy in Case 1 is chosen every year as the initial planning scenario for the next year. In Figure 7, the first year is the initial planning of the IEEE RTS-24 node system, which requires the initial investment in the energy storage equipment and the initial construction of the line. Therefore, the total cost of the initial year of planning is higher. In the second to fifth years, the planning cost also increases with the increase of the load level.

It can be seen from Figures 8 and 9 that the addition of flexible resources can reduce the investment cost of line expansion in the distribution network. This is because the downlink load in the flexible resource reduces the peak load of the system during operation, which in turn reduces the peak power transmitted by the line. At the same time, because electric vehicles can be used as a flexible energy storage in the virtual power station, excess photovoltaic power generation can be stored, thereby increasing the photovoltaic consumption rate. Therefore, the proposed model can effectively improve the economy of the planning process.

5.2.3. Analysis of Photovoltaic Absorption Results

In order to further verify the effectiveness of the proposed model in improving the PV uptake rate of the system, the comparison of the photovoltaic consumption results of the two cases on the third node of the typical day is shown in Figure 10.

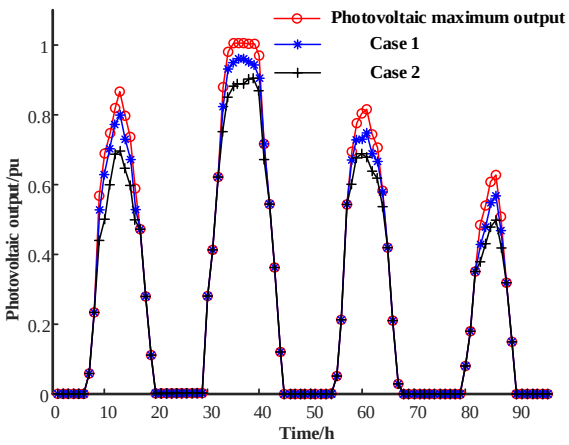

Figure 10. Comparison of PV consumption results on typical day of node 3.

It can be seen from the figure that when flexible resources are involved in planning, the actual PV output of the third node in the first year is more consistent with the maximum output curve than the actual PV output and the maximum output curve. This is because the addition of flexible resources such as distributed energy storage enables the photovoltaic power output of photovoltaic power station nodes to achieve on-site absorption. It reduces discarded light, improves the absorption rate of photovoltaics, and reduces power flow in the grid. While improving the economy of distribution network planning, the "peak cutting and valley filling" of power system is realized to a certain extent.

6. Conclusions

Aiming at the problem of quantifying the flexibility resources in virtual power plant in the existing literature, a distribution network planning method considering the flexibility of distributed energy resource in virtual power plant is proposed. The following conclusions can be drawn after setting corresponding examples for verification.

1. The planning method proposed in this paper analyzes the flexibility resources quantitatively and brings them into the planning process of distribution network. It effectively reduces the investment cost of line development and improves the economy of the planning process.
2. The proposed planning method utilizes the characteristic of flexible resources to transfer the peak load effectively and maintain the stable operation of the system. At the same time, distributed energy resource storage is used to improve the system's photovoltaic consumption rate.

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