Multi-objective optimal planning of urban virtual power plant based on electrical distance

Rui Zeng¹, Gaofeng Yang², Duyang Xie¹, Yi Zeng¹, Tianwen Zheng *³, Chengyun Zhang³, Lei Pan³

¹State Grid Chongqing Electric Power Company Economic and Technical Research Institute, Chongqing 404100, China
²State Grid Chongqing Electric Power Company, Chongqing 400014, China
³Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610213, China
zhengtianwen@tsinghua-eiri.org

Abstract. Currently, virtual power plants (VPP) in urban areas face problems such as over-dispersion of distributed power sources, insufficient source-load coordination. Traditional VPP planning method increases the difficulty in the operation and the dispatch of VPP. Therefore, this paper proposes a planning method for urban VPP that fully considers the coupling characteristics between the buses. From the distribution network to district to bus, a multi-objective bilevel optimization planning model for urban VPP is established. The upper-level planning model aims at minimizing the annual comprehensive cost, and derive the overall capacity of wind power turbine (WT), photovoltaic(PV), and energy storage system (ESS) of VPP in each district. The lower-level planning model aims at minimizing the network loss, and realizes the site selection and capacity allocation in each selected site. The case study based on the IEEE-33 standard system was carried out to verify the advancement and effectiveness of the proposed method.

1. Introduction
Vigorously developing renewable energy is an important measure for China to achieve the two aims of "reaching carbon emission peak" and "realizing carbon neutrality" [1-3]. However, with the increase in the proportion of distributed power sources and the increase in load, urban distribution networks face great challenges such as the expansion of peak-to-valley difference, curtailment of renewable energy, and poor power quality [4-5]. VPP could aggregate distributed power source, ESS and other resources to achieve coordinated control and participate in the operation of the power system. It plays an important role in promoting the consumption of renewable energy and ensuring the stability of urban power grid.

Due to the good application prospects of VPP, trial plants have been built around the world in the decade and related research has been carried out. For example, in 2009, Denmark launched an electric vehicle intelligent grid-connected project, considering the uncertainty of large-scale wind power output, and using virtual power plant technology to realize the management of intelligent charging and discharging of electric vehicles [7]. In 2019, Denmark launched a virtual power plant simulation trading trial, which achieved a peak regulation of 218,300 kW, and a maximum record of 99,000 kW in a single operation [8]. Literature [9] studied the coordinated dispatch of a VPP composed of a small
flexible nuclear power plant and an offshore wind farm. The output of different power supplies under different operation modes of VPP is analyzed. Literature [10] established a two-stage stochastic mixed integer programming model to optimize dispatch of VPP, and considered multi-scenario wind power output and the uncertainty of day-ahead market electricity prices. Literature [11] proposed an optimal quotation strategy based on the day-ahead market, considering the income, expenditure and operational constraints of VPP.

In summary, most of the current works mainly focus on the optimal dispatch VPP. There are only a few researches on the planning of VPP, and did not considering neither the electrical distance between a large number of distributed resources within the VPP. As a result, the actual dispatch of VPP is difficult, and the internal resource aggregation and coordination level are poor. Therefore, this paper proposes a multi-objective optimization planning method for urban VPP based on electrical distance. First, by introducing modularity indicators that consider electrical distance, the regional division of the urban distribution network is completed. On this basis, from the distribution network to district to bus, a multi-objective bilevel optimization planning model for urban VPP is established, and the genetic algorithm (GA) and particle swarm algorithm (PSO) are employed to solve the problem. The case study based on the IEEE-33 standard system was carried out to verify the advancement and effectiveness of the proposed method.

2. Regional division strategy of urban distribution network

2.1. Modularity index
This paper considers the coupling characteristics between buses in each zone of distribution network, and a modularity index based on electrical distance is proposed

$$\rho = \frac{1}{2f} \sum_i \sum_j \left( R_{ij} - \frac{\delta_i \delta_j}{2f} \right) \phi(i,j)$$  \hspace{1cm} (1)

where, $R_{ij}$ is the edge weight connecting bus $i$ and bus $j$, which is set to the electrical distance between the different buses. $\delta_i = \sum_j R_{ij}$ is the sum of all the edge weights connected to bus $i$. $\delta_j = \sum_i R_{ij}$ is the sum of all the edge weights connected to bus $j$. $f = \left( \sum_i \sum_j R_{ij} \right) / 2$ is the sum of all side rights of the distribution network. $\phi(i,j) = 1$, when bus $i$ and $j$ belong to the same zone, 0 otherwise.

2.2. Space electrical distance
Combined with the power flow equation of conventional distribution network system and considering the relationship between active power, reactive power, voltage and phase angle, the following equation(2) can be obtained

$$\Delta V = (L - DJK^{-1} N)^{-1} A \Delta Q = ADQ$$  \hspace{1cm} (2)

where, the node $a_{ij}$ of matrix $A$ is the value of the change in voltage at bus $i$ corresponding to the change in reactive power at bus $j$. When a change in reactive power occurs at bus $j$, $l_j = |\log(a_{ij} / a_{j})|$ is the ratio of the change in voltage at bus $j$ to the change in voltage at bus $i$.

So the spatial electrical distance between bus $i$ and $j$ is represented by equation (3).

$$R_{ij} = \left[ (l_1 - l_i)^2 + (l_2 - l_j)^2 + \cdots + (l_n - l_m)^2 \right]^{0.5}$$  \hspace{1cm} (3)
3. Two-level optimal planning model of urban VPP

3.1. Two-level planning framework of urban VPP

According to the proposed hierarchical planning strategy which from distribution network to district to bus in this paper, a two-level optimal planning model of urban VPP based on electrical distance is established, as shown in Figure 1. In the upper model, the optimization objective is to minimize the combined annual cost of the distribution network, where the decision variables are the capacity configuration of WT, PV and ESS in each zone. The lower model optimization objective is to minimize the average annual network loss and power purchase costs of the distribution network. The decision variables are the access capacity of WT and PV at the bus within each subzone, the location of the ESS and the power of the ESS. The PSO is used to solve the optimization model proposed in this paper.

![Fig.1. Two-level planning framework of urban VPP](image)

| Upper level optimization | Lower level optimization |
|--------------------------|--------------------------|
| **Optimal object**: Annual installation cost $O_1$, Annual operating and maintenance costs $O_2$, Main network electricity purchase cost $O_3$ | **Decision variables**: The capacity of photovoltaic, wind power and energy storage connected to each partition |
| **Objective function**: $\min O = O_1 + O_2 + O_3$ | **St. function** $(8)$ - $(13)$ |
| Virtual power plant capacity configuration scheme in each scheme | Average annual network loss cost of distribution network |
| Zone 1: The WT, PV, ESS and energy storage power of nodes in each partition | Zone N: The WT, PV, ESS and energy storage power of nodes in each partition |
| **Objective function**: $\min P_{int}$ | **St. function** $(15)$ - $(18)$ |

3.2. Upper Planning Model of Urban VPP

3.2.1. Objective function. The objective function of the upper optimization model mainly considers the investment cost, operation and maintenance cost of distributed power and energy storage in the VVP as well as the power purchase cost and network loss cost of distribution network

$$\min O = O_1 + O_2 + O_3$$

where $O_1$ represents investment costs for WT, PV and ESS. $O_2$ represents the operation and maintenance costs of WT, PV and ESS. $O_3$ represents the purchases and network losses costs of distribution network.

According to engineering practice, the installed costs of WT, PV and ESS in the engineering applications can be considered as a single value function of the installed capacity, Therefore, the installed costs of WT, PV and ESS within a VPP can be described as equation (5).

$$O_1 = \sum_{s=1}^{N} \frac{\alpha(1+\mu)^\alpha}{(1+\mu)^\alpha-1} \left( E_s^{PV}C_{PV} + E_s^{WT}C_{WT} + E_s^{BA}C_{BA} \right)$$

where $N$ is the number of zones in the distribution network, $\mu$ is the discount rate, $\alpha$ is the operating life of the equipment, $E_s^{PV}$, $E_s^{WT}$ and $E_s^{BA}$ are the installed capacities of PV, WT and ESS in zone $s$ respectively. $C_{PV}$, $C_{WT}$ and $C_{BA}$ are the installation costs per unit capacity for PV, WT and ESS respectively.

The operating costs of WT, PV and ESS can be represented by equation (6)

$$O_2 = \sum_{s=1}^{N} \left[ E_s^{PV}G_{PV} + E_s^{WT}G_{WT} + E_s^{BA}G_{BA} \right]$$

where $G_{PV}$, $G_{WT}$ and $G_{BA}$ are the operating costs per unit of capacity for PV, WT and ESS respectively.
The power purchase cost of distribution network, active power loss cost of distribution network line can be expressed by equation (7).

$$O_i = 365 \left( \sum_{t=1}^{N_t} \left( \sum_{i=1}^{N_i} p_{i,t}^{prod} + p_{i,t}^{loss} - \sum_{i=1}^{N_i} p_{i,t}^{PV} - \sum_{j=1}^{N_j} p_{j,t}^{WT} \right) C_{i}^{ELE} + p_{i,t}^{loss} C_{i}^{Loss} \right)$$

where $p_{i,t}^{prod}$, $p_{i,t}^{PV}$ and $p_{i,t}^{WT}$ are the active power of load, photovoltaic and wind power at the $i$ bus at time $t$ of a typical day, respectively. $N_{node}$ is the number of buses in the distribution network. $C_{i}^{ELE}$, $C_{i}^{Loss}$ are the electricity purchase price and the grid loss electricity price at time $t$ respectively on a typical day.

### 3.2.2. Constraint condition

The WT capacity constraints in each zone of the distribution network can be expressed by equation (8).

$$0 \leq E_{0,s}^{WT} \leq \sum_{j=1}^{N_j} E_{0,s,j}^{WT,max}$$

where $E_{0,s}^{WT}$ is the WT capacity in zone $s$. $E_{0,s,j}^{WT,max}$ is the maximum WT capacity of each bus in zone $s$.

The PV capacity constraints in each zone of the distribution network can be expressed by equation (9).

$$0 \leq E_{0,s}^{PV} \leq \sum_{j=1}^{N_j} E_{0,s,j}^{PV,max}$$

where $E_{0,s}^{PV}$ is the PV capacity in zone $s$. $E_{0,s,j}^{PV,max}$ is the maximum installed PV capacity of each bus in zone $s$.

The ESS capacity constraints in each zone of the distribution network can be expressed by equation (10).

$$0 \leq E_{0,s}^{ESS} \leq E_{0,s}^{ESS,max}$$

where $E_{0,s}^{ESS}$ is the ESS capacity in zone $s$. $E_{0,s}^{ESS,max}$ is the maximum ESS capacity of each bus in zone $s$.

The power constraints of branches between different areas of the distribution network can be expressed by equation (11).

$$|p_{l,t}| \leq p_{l,t}^{max}$$

where $p_{l,t}$ is the interaction constraint for branch $l$ at time $t$. $p_{l,t}^{max}$ is the maximum interactive power of branch $l$.

### 3.2.3. Wind and photovoltaic power generation model

The PV output can be calculated from its operating temperature, light intensity and the manufacturer's calibration parameters.

$$P_{PV}^{EV} = E_{0,s}^{PV} \times \frac{G_s}{G_{STC}} \times \left[ 1 + k(T_c - T_{STC}) \right]$$

where $E_{0,s}^{PV}$ is the rated installed PV capacity. $G_s$ is the solar irradiance when the solar panel is in operating. $T_c$ is the actual operating temperature of the solar panel. $k$ is the power temperature coefficient, $k=1000/W/m^2$. $G_{STC}$ is the test irradiance of the PV, $G_{STC} = 1000 W/m^2$.

The wind power output can be calculated using equation (13)

$$P_{WT}^{EV} = \begin{cases} E_{0,s}^{WT} (v_c - v_i)(v_i - v_{i-1}), & v_{i-1} < v_i \leq v_c \\ E_{0,s}^{WT} v_c, & v_i < v_{i-1} \\ 0, & v_i > v_{i-1} \end{cases}$$
where $v_c$ is the cut-in wind speed, $v_r$ is the nominal wind speed, $v_{co}$ is the cut-out wind speed, $v_t$ is the wind speed at which the wind turbine is operating, $E_{WT}^0$ is the rated power of the wind turbine.

### 3.3. Lower Planning Model of Urban VVP

#### 3.3.1. Objective function

The objective function of the upper optimization model is mainly consider the minimum sum of power loss and power purchase capacity of the entire distribution network.

$$\min P_{upper} = 365 \sum_{t=1}^{T_P} \left( \sum_{j=1}^{N} P_{loss,j,t} + P_{tg}^t \right)$$  \hspace{1cm} (14)

where $P_{loss,j,t}$ is the network loss of each branch at time $t$, $P_{tg}^t$ is the power purchase capacity of the distribution network at time $t$.

#### 3.3.2. Constraint condition

The PV installation capacity constraint of each node in each zone can be expressed by equation (15)

$$E_{PV,s}^j = \sum_{j=1}^{N} E_{PV,s,j}$$  \hspace{1cm} (15)

where $E_{PV,s,j}^j$ is the PV installation capacity of bus $j$ in zone $s$, $E_{PV,s}^j$ is the total installed capacity of PV in area $s$.

The WT installation capacity constraint of each node in each zone can be expressed by equation (16)

$$E_{WT,s}^j = \sum_{j=1}^{N} E_{WT,s,j}$$  \hspace{1cm} (16)

where $E_{WT,s,j}^j$ is the WT installation capacity of bus $j$ in zone $s$, $E_{WT,s}^j$ is the total installed capacity of WT in area $s$.

Only one bus for energy storage is considered in each area, so the ESS installation capacity constraint of each zone can be expressed by equation (17)

$$E_{B,s}^{BA} = E_{B,s}^{BA}$$  \hspace{1cm} (17)

where $E_{B,s,j}^{BA}$ is the ESS installation capacity of bus $j$ in zone $s$, $E_{B,s}^{BA}$ is the total installed capacity of ESS in area $s$.

Power flow constraint of distribution network can be expressed by equation (18)

$$\begin{bmatrix} P_i = U_i \sum_{j=1}^{N} \left( G_{ij} \cos \theta_j + B_{ij} \sin \theta_j \right) \\ Q_i = U_i \sum_{j=1}^{N} \left( G_{ij} \sin \theta_j - B_{ij} \cos \theta_j \right) \end{bmatrix}$$  \hspace{1cm} (18)

where $P_i, Q_i$ are active and reactive power injection of bus $i$ and $j$ respectively, $U_i, U_j$ are Voltage amplitude of bus $i$ and $j$ respectively, $G_{ij}, B_{ij}$ are Branch admittance of bus $i$ and $j$ respectively, $\theta_j$ is the voltage phase angle difference of bus $i$ and $j$.

### 4. Case study

The calculation example in this paper adopts the IEEE-33 node standard power distribution system, and the standard voltage of the system is 12.66KV. The installation costs and operating costs of PV, WT, and energy storage are shown in Table 1. Wherein, the charge and discharge power of the energy storage is divided into 0.95, and the operating charge range of the energy storage is (0.2, 0.8). The solar irradiance, wind speed, typical daily load level in the zone where the distribution network is...
located are used as input data of the system as shown in Figure 2 to 5. The input wind speed, rated wind speed and cut wind speed of the fan are 2.5, 11 and 60 m respectively.

Table 1 Investment and operation cost of each Species PV WT Battery

|                  | Cost of installation       | Cost of Annual operating |
|------------------|--------------------------|-------------------------|
| PV               | 14800yuan/kW             | 90yuan/kW               |
| WT               | 3850yuan/kW              | 37yuan/kW               |
| Battery          | 6250yuan/kW              | 100yuan/kW              |

4.1. Regional division scheme of urban distribution network

Based on the proposed modularity division index considering electrical distance, the regional division model of urban distribution network is established and solved by genetic algorithm. The initial population number N was set as 200, the maximum iteration number IMAX is 50, the crossover probability PC is 0.3, the mutation probability PM is 0.05. The results of distribution network partition are calculated under three schemes with the number of zone partition from 3 to 5. Table 2 shows the modularity index of the distribution network under different division schemes. It can be seen from Table 2 that as the number of regional divisions increases, the modularity index of the distribution network decreases. This is because the increase in the number of partitions leads to the decrease of connectivity between nodes, coefficient between nodes $\Phi(i, j)$ is 0, as a result, the modularity index of the entire distribution network decreases. The node distribution of each zone under different division schemes is shown in Figure 6.
Table 2 Modularity index of urban distribution network under different division schemes

| number of zone divisions | 3     | 4     | 5     |
|--------------------------|-------|-------|-------|
| modularity index         | 0.6681| 0.4752| 0.3243|

Fig. 6. Schematic diagram of urban power distribution area division

4.2. Distribution of annual average cost and capacity of virtual power plants in urban areas under different division schemes

In order to highlight the advantages of the proposed multi-objective optimal planning of urban virtual power plant based on electrical distance, this paper also constructs a single-level planning model (SLPM) for urban VPP without partitioning the distribution network. The comprehensive cost of distribution network under different planning schemes is shown in Table 3. Among them, DS1 to DS3 refer to the multi-objective planning model of the urban virtual power plant in the case of 2 to 5 regional divisions. It can be seen from Table 3 that before the planning, the load demand of the distribution network is all supplied through the purchase of electricity from the main network, and the comprehensive cost of the distribution network is high. After the planning, the distribution network comprehensive costs of different schemes are reduced, and the comprehensive costs of DS3 10.4% less than without planning scheme. Among Table 3, the distribution network operation costs of schemes 1 to 3 are lower than the single-layer planning scheme, and accounting for 99.5%, 97.4% and 90.3% of single-layer planning schemes respectively. The operation cost decreases with the increase of the number of divisions of the distribution network. So it can be seen that the use of the planning model proposed in this paper can effectively reduce the comprehensive cost of the distribution network.

Figure 7 shows the capacity distribution of urban virtual power plants in the case of division scheme 1 to division scheme 3. It can be seen from Figure 7 that the total capacity of VPP in division schemes 1 to 3 is 1074kW, 1302 kW and 1558Kw respectively. On the whole, the virtual power plant capacity planning method based on electrical distance increases the total capacity of PV, WT and ESS in the distribution network, improves the distribution of PV, WT and ESS in each zone, and thus improves the economy of the distribution network.
Table 3 The average annual comprehensive cost of urban distribution network under different planning schemes

| Cost | Without planning | SLPM | DS1 | DS2 | DS3 |
|------|------------------|------|-----|-----|-----|
| $Q_1$ | 0                | 0.69 | 0.58 | 0.51 | 0.77 |
| $Q_2$ | 0                | 0.11 | 0.10 | 0.11 | 0.14 |
| $Q_3$ | 63.2             | 61.9 | 61.7 | 60.5 | 55.7 |
| $Q_4$ | 63.2             | 62.7 | 62.4 | 61.1 | 56.6 |

4.3. Capacity distribution and output characteristics of virtual power plants in urban areas of various zones

Figure 8 shows the capacity distribution of VPP in each zone of the urban distribution network in the case of division scheme 3. It can be seen from Figure 6 that the capacity of each device in the virtual power plant in different partitions is quite different. The total capacity of VPP in zone 1 to 5 is 862kW, 163 kW, 185 kW, 169 kW and 179kW respectively. Among them, the installed capacity of PV and ESS in zone 1 is higher than that in other zones. This is because zone 1 has more internal nodes and can accommodate more virtual power plant installed capacity.

Figure 9 shows the external output characteristics of the VPP in each zone of the urban distribution network in the case of division scheme 3. It can be seen from Figure 9 that because the VPP contains ESS, so compared to conventional power sources, the output of VPP has the characteristics of two-way power regulation, which can further promote the consumption of renewable energy and ensure the stable operation of the distribution network. Among them, the power adjustment range of the VPP in zone 1 is much higher than that of other zones. This is because the energy storage capacity in partition 1 is much higher than that of other partitions.

5. Conclusion

An urban VPP planning method is proposed in this paper that fully considers the coupling characteristics of the buses. A two-level planning model for urban VPP from the distribution network to the district to the busbar is established. Furthermore, capacity allocation and site selection
optimization of PV, WT and ESS of VPP in each zone were carried out. The following conclusions can be obtained through the analysis of the numerical examples.

1. The proposed planning method improves the acceptance ability of distribution network to distributed power, which reduces the burden of main network and connecting line, and then the operation economy of distribution network is improved.

2. The comprehensive operating cost of the distribution network decreases with the increase in the number of divided zones.

3. When the number of regional divisions is 5, the comprehensive operating cost of the distribution network is reduced by 10.4% compared to the initial plan.

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