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Grid-based Optimal Co-Planning of Urban Distribution Network and Electric Vehicle Charging Stations: A Case Study in Shanghai

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ABSTRACT

Electric vehicles (EVs) have great impacts on power distribution networks due to their spatio-temporal characteristic, especially in urban areas. This paper proposes a framework for optimal planning of urban distribution network (UDN) and electric vehicle charging stations (EVCSs), in which the geographic information system (GIS) is combined to optimize investment decisions. By using hierarchical clustering and Voronoi diagram, the planning area is divided into several sub-areas. All the sub-area is converted into grid networks based on GIS, on which the EVs' actual temporal charging demand is analyzed. The proposed mixed integer planning model utilizes the second-order cone programming for UDN and grid-based site selection of EVCS by considering the spatio-temporal characteristic of EVs. Case studies on an urban area in Shanghai, China demonstrate the effectiveness of the proposed method.

Keywords: electric vehicle, urban distribution network, mixed integer planning, geographic information system

NONMENCLATURE

Abbreviations

EVs	Electric Vehicles
UDN	Urban Distribution Network
EVCSs	Electric Vehicle Charging Stations
GIS	Geographic information System
CO_2	Carbon Dioxide
DSO	Distribution System Operator
MISOCP	Mixed integer second-order cone programming

Symbols

γ	Discount rate
α	Annualized factor
φ	Planning year
c	Construction cost
L	Line set
N	Node set
l	Index of lines in set L
i, j	Index of nodes in set N
x_l	Binary variable for cable construction
y_l	Binary variable for cable operation
z_i	Binary variable for EVCSs construction
P_{ij}	Real power flow from node i to j
Q_{ij}	Reactive power flow from node i to j
v_i	Voltage magnitude square of node i
l_{ij}	Current magnitude square from node i to j
p_i	Real power injection at node i
q_i	Active power injection at node i
p_i^{ev}	Real power of EVs at node i
q_i^{ev}	Active power of EVs at node i
$I_{\max}$	Max current in cables
S_{ij}	Max transmission of cables
β_{ij}	Binary variable indicating whether node j is the parent of node i

1. INTRODUCTION

Global warming has become a major concern in the early 21st century. The Paris Agreement was adopted in

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2015 under the pressure of climate change [1]. After that, the dual carbon goals were proposed in 2020 by China [2], which aims to peak carbon emission by 2030 and achieve carbon neutrality before 2060. To tackle the greenhouse gas, mainly carbon dioxide (CO_2), many new technologies and industrial applications have emerged, especially in the transportation and electricity areas. According to the estimation in [3], both are the main contributors to carbon emissions, which are 27% and 25%, respectively.

Also, the fossil sources dilemma leads to a dramatic increase in electric vehicles (EVs), which is supposed to be at least 80 million by 2030 in China. With the rapid expansion of cities and explosion of EVs [4], the electric vehicle charging stations (EVCSs) have become an important part of the urban distribution network (UDN). However, the entities of UDN and EVCSs are usually different [5]. The large amounts of EVs have great impact to the reliability of UDN. Also, the site selection of EVCSs is highly related to the social-cyber system [6]. So, the co-planning of UDN and EVCSs could effectively alleviates the distribution system operators (DSOs) economy and social welfare pressure.

Recent years, there were several reviews of UDN with EVCSs [3]-[6]. The potential of EVs has been fully explored to achieve a coordinating planning strategy of UDN and EVCSs. In [7], the siting and sizing of EVCSs on coupled transportation and power networks is studied and a mixed integer second-order cone programming (MISOCP) model was proposed. Also, a comprehensive model for the expansion planning of urban electrified transportation networks was proposed in [8], which determined the best investment strategy for UDN and transportation networks. In [9], a novel MISOCP model was proposed to minimize the annualized social cost of whole EVCSs integrated in UDN. A non-linear model for coordinated charging of EVs within a local UDN was proposed and analyzed in [10]. All the above papers considered the coordination of EVs with transportation, power system, building management, etc. However, the co-planning of UDN and EVCSs considering spatio-temporal characteristic of EVs combined with geographic information system (GIS) still needs further explored.

In this paper, the TransBigData is utilized to grid the planning area and analyze the characteristics of EVs based on hierarchical clustering and Voronoi polygon. After that, an optimal co-planning model of UDN and EVCSs is proposed to determine the investment decisions of cables and stations. The whole model is formulated as an MISOCP problem which can be solved by commercial solvers. The main contributions are as follows:

1) A grid-based method combined with GIS and TransBigData is proposed to analyze the spatio-temporal characteristic of EVs.
2) An optimal co-planning model for UDN and EVCSs is proposed to fulfill the economy and social welfare of EVCSs while ensuring the reliability of UDN.

In the remainder of this paper, Section 2 introduces the framework of the proposed method. Case studies are discussed in Section 3. Finally, relevant conclusions and future works are drawn in Section 4.

2. MODEL FORMULATION

Fig. 1 illustrates the proposed co-planning model for UDN and EVCSs. The framework consists of three parts. First, the raw data of EVs in Shanghai is aggregated and the UDN follows the IEC 61970 standard. Second, the sub-areas are divided to analyze the spatio-temporal characteristic of EVs. Third, the optimal co-planning model of UDN and EVCSs is formulated to determine the investment decisions.

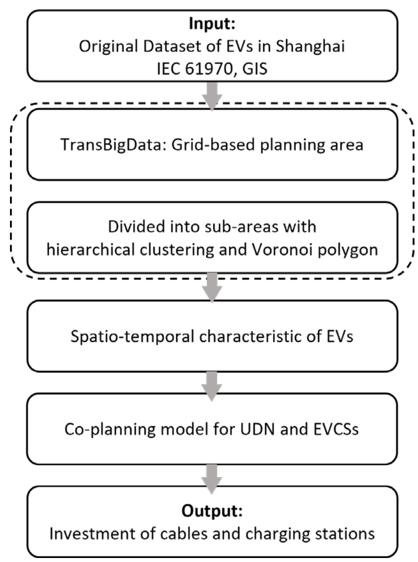

Fig. 1. Framework of the proposed method

2.1 Grid-based analysis of EVs

The preparation and preprocess for big data of EVs is mainly based on the TransBigData. A Python package developed for transportation spatio-temporal big data processing and analysis, which can gird, analyze, and visualize the planning area.

First, Voronoi diagram [11] is introduced to segment the planning area into sub-areas close to each of a given set of objects. In such case, these objects are just finitely buses of the distribution network. For each bus there is a corresponding sub-area, called Voronoi cell, consisting of all points closer to that seed than to any other. Then, the planning area, several practical blocks in Shanghai, is divided and each sub-area is ready for further analysis and clustering.

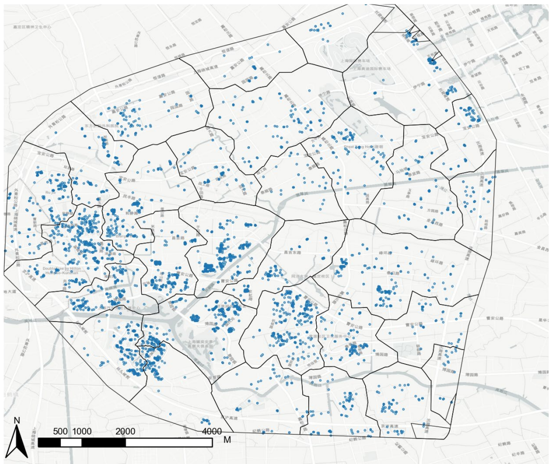

Fig. 2. Voronoi cell of the planning area

Second, EVs information is extracted from data, such as vehicle type, timestamp, battery capacity, charging state, SOC, GPS, etc. After that, the charging loads of EVs in each grid could be mapped by TransBigData. However, the grids are often too dense to be representative. The hierarchical clustering is used to aggregate the charging loads of EVs corresponding to each sub-area. The typical week charging load of EVs is shown below.

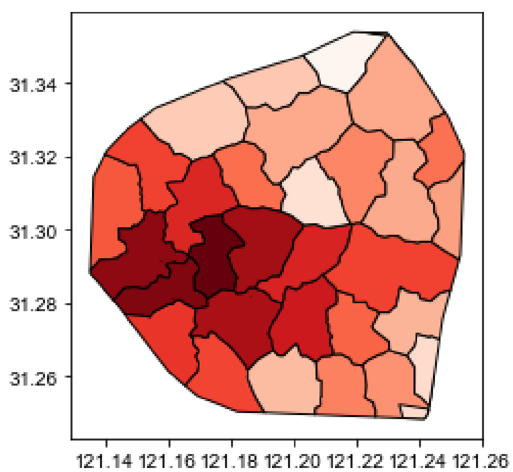

Fig. 3. Charging load of EVs

2.2 Optimal co-planning model

The optimal co-planning model of UDN and EVCSs is formulated as an MISOCP. The objective minimizes the annualized investment cost as follows.

$$f = \alpha \cdot C_{inv}$$

$$\alpha = \frac{\gamma(1+\gamma)^{\varphi}}{(1+\gamma)^{\varphi}-1} \tag{1}$$

$$C_{inv} = \sum_{l \in L} c_l x_l + \sum_{i \in N} c_i z_i \tag{2}$$

The investment cost C_{inv} is multiplied by the annualized factor α over the facility lifetime φ and consists of two parts. The first part is the cable construction decision variables x_l times corresponding cost c_l. The second part is the summation of EVCSs construction decision variable z_i times corresponding cost c_i.

$$P_{ij} = p_i - p_i^{ev} - p_i^{shed} + \sum_{h:h \to i} P_{hi} \quad \forall (i,j) \in L \tag{3}$$

$$Q_{ij} = q_i - q_i^{ev} - q_i^{shed} + \sum_{h:h \to i} Q_{hi} \quad \forall (i,j) \in L \tag{4}$$

$$v_j = v_i - 2(rP_{ij} + xQ_{ij}) + (r^2 + x^2) l_{ij} \quad \forall (i,j) \in L \tag{5}$$

$$\left\| \begin{matrix} 2P_{ij} \\ 2Q_{ij} \\ l_{ij} - v_i \end{matrix} \right\| \le l_{ij} + v_i \quad \forall (i,j) \in L \tag{6}$$

$$\underline{P_{ij}} \le P_{ij} \le \overline{P_{ij}} \quad \forall (i,j) \in L \tag{7}$$

$$\underline{Q_{ij}} \le Q_{ij} \le \overline{Q_{ij}} \quad \forall (i,j) \in L \tag{8}$$

$$\underline{U_i}^2 \le v_i \le \overline{U_i}^2 \quad \forall i \in N^{load} \tag{9}$$

$$0 \le l_{ij} \le \overline{I_{\max}}^2 \quad \forall (i,j) \in L \tag{10}$$

$$P_{ij}^2 + Q_{ij}^2 \le (1 - y_l) S_{ij}^2 \quad \forall (i,j) \in L \tag{11}$$

The Eq.(3) – Eq.(6) is the SOCP of UDN [12]. The real and reactive power flow are controlled by Eq.(7) – Eq.(8). The voltage magnitude of each node is limited by Eq.(9). The current and transmission capacity of lines are denoted by Eq.(10) – Eq.(11).

$$\sum_{i \in N(j)} x_l \ge 2 \quad \forall l \in L \tag{12}$$

$$y_l \le x_l \quad \forall l \in L \tag{13}$$

$$\sum_{(i,j) \in L} y_l = |N^{load}| \quad \forall l \in L \tag{14}$$

$$\beta_{ij} + \beta_{ji} = y_l \quad \forall (i,j) \in L \tag{15}$$

$$\sum_{j \in N(i)} \beta_{ij} = 1 \quad \forall i \in N^{load} \tag{16}$$

$$\sum_{j \in N(0)} \beta_{0j} = 0 \tag{17}$$

Eq.(12) indicates the degree of each load node should larger than two according to the ring design of UDN. Intuitively, Eq.(13) indicates that each line can operate only if constructed. The number of load nodes is denoted by $|N^{load}|$ and Eq.(14) is a necessary condition for the radiality of UDN. However, it is not sufficient [13]. Additional constraints for the radiality of UDN are needed. The spanning tree constraint [14] is an ideal way to guarantee the radiality of UDN by introducing two binary variables β_{ij} and β_{ji}. Eq.(15) ensures that the operated line l is in the spanning tree if either node j is the parent of node i or node i is the parent of node j. Eq.(16) – Eq.(17) indicate that each node has exactly one parent node except substation nodes, while the substation has no parent node.

3. CASE STUDIES

A practical case based on urban blocks in Shanghai is modified to test the proposed method. The model is developed in MATLAB with YALMIP [15]. The simulations are implemented in a laptop with an Intel Core i7-10750H processor at 2.60 GHz and 32 GB of RAM using Gurobi 9.5.2. The cable construction cost and electricity price are 0.6M/km and 0.045/MWh. The discount rate γ is set to 5% and the planning year φ is 10 years.

3.1 Discussion on planning results

The co-planning results of UDN and EVCSs in the urban blocks of Shanghai is shown in Fig. 4. The Voronoi cell is determined, and each seed is the bus of UDN. The red square is the substation. The purple lines indicate the cable in operation, the green dotted lines indicate the cable is constructed but not in operation. The site selection for EVCSs is yellow squares. The mesh network of UDN is promising in improving the reliability. So, the close loop construction, open loop operation criterion is conducted in the UDN. Also, the cable routing results are listed with continuous number sequences like SUB-18-15-12-22-25. The construction cost of UDN and EVCSs for the planning area is 417.9M.

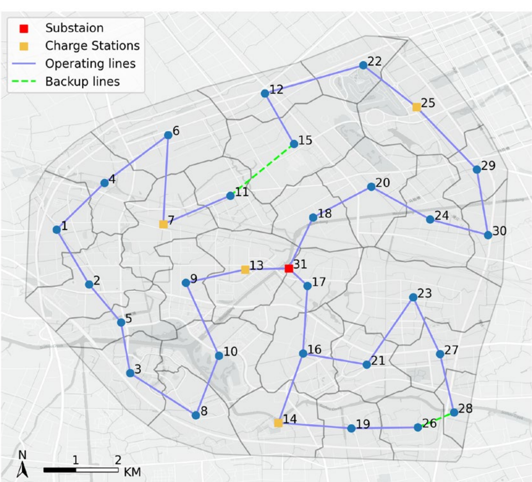

Fig. 4. Co-planning results of UDN and EVCSs

3.2 Sensitive analysis

The fluctuation of load demand and spatio-temporal characteristic of EVs could result in the topology change and site selection of EVCSs. If the penetration rate of EVs is doubled, the construction of UDN and site selection of EVCSs could vary. Compared with Fig. 4, Fig. 5 illustrates the co-planning results of the UDN and EVCSs with doubled penetration rate. The topology of UDN changes and the site selection of EVCSs transfer to the sub-area with higher penetration rate of EVs.

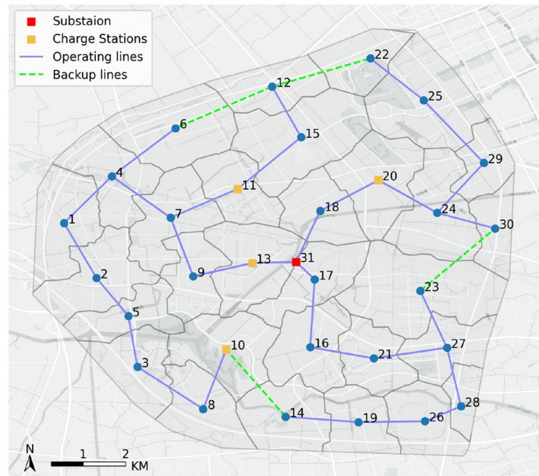

Fig. 5. Co-planning results under doubled penetartion rate

4. CONCLUSION

In this paper, a grid-based optimal co-planning model of UDN and EVCSs is proposed. The Voronoi diagram and hierarchical clustering are conducted to analyze the spatio-temporal characteristic of EVs in the planning area. Then, an MISOCP model is proposed to solve the co-planning of UDN and EVCSs. The case studies in Shanghai show the advantages of the of the proposed method, which can alleviate the economy and social welfare of DSOs. The mesh network of UDN guarantees the reliability and the EVCSs is invested to meet the electrification process of transportation. For future work, the V2G characteristic of EVs should be considered and further explored in urban areas.

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