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Robust Joint Planning of Electric Vehicle Charging Infrastructures and Distribution Networks

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***Abstract*—The electric vehicles (EVs) are developed rapidly due to the demand of fossil fuel depletion and environmental pressure. However, as a flexible and clean resource, EV charging is full of uncertainty. With its large-scale integration in grid, the reliable operation of distribution network is challenged, especially when there is a large penetration of distributed generation (DG) in the system as well. As a result, how to perform the distribution network planning to ensure its reliable operation under the uncertainties is an urgent need for the current grid development. Based on this, considering the uncertainty of EV charging demand and DG supply, a robust joint planning model of EV charging infrastructures and distribution networks is proposed in this paper to adapt to the grid development. Big-M technique and second-order cone relaxation technique are adopted to linearize the non-linear part. Finally, the effectiveness and scalability of the proposed method is illustrated by the numerical case studies.**

***Keywords*—*electric vehicle, uncertainty, robust optimization, distribution network,* charging infrastructures**

I. Introduction

Under the rise of dual environmental and energy pressure, the demand for low carbon and energy saving is higher and higher. According to incomplete statistics, the carbon emission of the transportation area is about 30% of the social emissions, and more than 90% of greenhouse gas and air pollutants are from the city. Therefore, it is important to reduce emissions in the transportation area to achieve the goal of "2030 carbon peak, 2060 carbon neutral". And as a result, electric vehicles (EVs) have developed a lot. However, due to the subjective and uncertain characteristics of EV users, the large-scale EV integration will bring operation risks to the grid, especially when there is high penetration of distributed generation (DG) in the distribution network as well. Hence, how to perform the distribution network planning to ensure its reliable operation is an urgent need for the current grid development.

In the research of planning of EV distribution network topology, DG and electric vehicle charging station (EVCS), the economy is usually set as the optimization target to obtain the optimal planning scheme. In [1], an EVCS planning model with the goal of minimizing the total cost of investment and operation was proposed considering the charging demands and the acceptance capacity of distribution network. Reference [2] proposed an optimal expansion strategy for both transportation network and distribution network considering the steady-state distribution of traffic flow. In [3], an optimal fast-charging station planning model considering EV users' convenience, economic benefits and the environmental effects was developed. In [4], a multi-objective collaborative planning model was established to minimize the investment and operation cost as well as the unbalanced traffic flows. However, the uncertain factors such as the EV charging demand and DG output are not considered during the planning process.

There is a large number of uncertain factors during distribution network planning process, including the EV user charging demand, DG output and so on. The existing research is mainly focused on the stochastic optimization (SO) and robust optimization (RO) [5]. The stochastic optimization is usually established by a scenario expected value [6] or a chance-constrained programming [7]. For the former, a large number of scenario data is required. Hence, the calculation efficiency is low and it is difficult to be applied to large-scale optimization problems. For the chance-constrained programming, it is hard to obtain accurate probability density distribution. And it belongs to the non-convex planning, whose optimization process is complicated. In contrast, planning based on RO is easy to optimized and do not need to be limited by the probability distribution. Therefore, it is more advantageous and widely used in handling uncertain factors. However, there is still few research in the area of the collaborative planning of EVCS and distribution network. In

[8], a tri-level investment planning model was developed considering the physical and financial data uncertainty in load demand. Reference [9] established a two-levee robust planning model of active distribution network with a sequential uncertain set. However, the uncertainty of EV charging demand in the distribution network is not considered during the planning process.

Based on the above discussion, considering the uncertainty of EV charging demand and WTG output, this paper proposed a robust optimization of distribution network planning model with EVCS sizing and siting decision. The nonlinear part is linearized by Big-M method and second-order cone relaxation technique [10]. And for the second-stage min-max-min optimization problem, column and constraint generation algorithm is adopted to solve the robust optimization model. Finally, an improved coupled system are adopted to perform the case studies.

The remainder of this paper is organized as follows. The robust planning model is introduced in Section II. Section III presents the joint planning model of EV charging infrastructures and distribution networks. The effectiveness and scalability of the proposed planning method are tested in Section IV. Section V concludes this work.

II. THE ROBUST OPTIMIZATION MODEL

A. Uncertain Set

For uncertain parameters in the optimization process, the robust optimization method is adopted to make the optimal planning scheme in the worst scenario. The uncertain variable is optimized freely in the uncertain interval, which is expressed as follows:

$$\tilde{P}_{i,t}^{\text{EVload}} \in [(1-\sigma)P_{i,t}^{\text{EVload\_pre}},(1+\sigma)P_{i,t}^{\text{EVload\_pre}}] \tag{1}$$

$$\tilde{P}_{i,t}^{\text{WTG}} \in [(1-\sigma)P_{i,t}^{\text{WTG\_pre}},(1+\sigma)P_{i,t}^{\text{WTG\_pre}}] \tag{2}$$

where $\tilde{P}_{i,t}^{\text{EVload}}$ and $\tilde{P}_{i,t}^{\text{WTG}}$ are the uncertain variable, i.e., EV charging load and WTG output. $P_{i,t}^{\text{EVload\_pre}}$ and $P_{i,t}^{\text{WTG\_pre}}$ are the corresponding forecasted power, respectively. σ is the uncertainty of the variation range.

B. Robust Optimization Planning Model of Distribution Network

Considering the uncertainty of wind power and electric vehicle charging demand, a planning model is proposed to improve the operation economy of distribution network. The RO planning model can be expressed as follows:

$$\min_{x} \max_{y\in Y} \; Total\,\mathrm{Cos}t \tag{3}$$

$$\text{s.t.} \quad A(x)=0 \tag{4}$$

$$B(x)\le 0 \tag{5}$$

where $Total\,\mathrm{Cos}t$ is a comprehensive expression of the investment cost and operation cost of the distribution network. u is the uncertain variable, i.e., WTG output and EV charging demand. x is the decision variable, which is divided into the investment decision variable and operation decision variable. The investment decision variables include the planning scheme of EVCS, the substation, WTG, the charging pile and the feeder. The operation decision variables include the generation power, bus voltage, branch current, etc. Equation (4) is the equality constraint, which includes the power balance constraint, investment constraint, etc. Equation (5) is the inequality constraint, including the security constraints, capacity limit and so on.

III. THE JOINT PLANNING OF EV CHARGING INFRASTUCTURES AND DISTRIBUTION NETWORKS

A. Objective Function

This study considers the joint planning of EV charging infrastructures and distribution networks with the target of the highest economic benefits. The economic costs involve investment cost and operation cost. The formulations are as follows:

$$\min \quad Total\,\mathrm{Cos}t = \mathrm{Cost}^{\text{inv}} + \mathrm{Cos\,t}^{\text{ope}} \tag{6}$$

$$\mathrm{Cost}^{\text{inv}} = \mathrm{Cost}_{\text{sub}}^{\text{inv}} + \mathrm{Cost}_{\text{line}}^{\text{inv}} + \mathrm{Cost}_{\text{EVCS}}^{\text{inv}} + \mathrm{Cost}_{\text{WTG}}^{\text{inv}} + \mathrm{Cost}_{\text{chargingpile}}^{\text{inv}} \tag{7}$$

$$\mathrm{Cost}^{\text{ope}} = \mathrm{Cost}_{\text{sub}}^{\text{ope}} + \mathrm{Cost}_{\text{WTGshed}}^{\text{ope}} + \mathrm{Cost}_{\text{EVloadshed}}^{\text{ope}} + \mathrm{Cost}_{\text{loss}}^{\text{ope}} + \mathrm{Cost}_{\text{line}}^{\text{ope}} \tag{8}$$

1) Investment Cost

$$DR = \frac{r_0(1+r_0)^m}{r_0(1+r_0)^m - 1} \tag{9}$$

$$\begin{aligned} \mathrm{Cost}_{\text{sub}}^{\text{inv}} &= DR^{sub} \sum_{i\in\Omega_{\text{sub\_new}}} \mathrm{Cost}^{\text{sub\_new}} x_i^{\text{sub\_new}} \\ &+ DR^{sub} \sum_{i\in\Omega_{\text{sub\_ext}}} \mathrm{Cost}^{\text{sub\_ext}} x_i^{\text{sub\_ext}} \end{aligned} \tag{10}$$

$$\mathrm{Cost}_{\text{chargingpile}}^{\text{inv}} = DR^{\text{pile}} \sum_{i\in\Omega_{\text{pile}}} \mathrm{Cost}^{\text{pile}} x_i^{\text{pile}} \tag{11}$$

$$\mathrm{Cost}_{\text{line}}^{\text{inv}} = DR^{\text{line}} \sum_{ij\in\Omega_{\text{line}}} \mathrm{Cost}^{\text{line}} Lo_{ij} x_{ij}^{\text{line}} \tag{12}$$

$$\mathrm{Cost}_{\text{EVCS}}^{\text{inv}} = DR^{EVCS} \sum_{i\in\Omega_{\text{EVCS}}} x_i^{\text{EVCS}} (\mathrm{Cost}_i^{\text{EVCS\_fix}} + s_i \mathrm{Cost}_i^{\text{EVCS\_var}}) \tag{13}$$

$$\mathrm{Cost}_{\text{WTG}}^{\text{inv}} = DR^{WTG} \sum_{i\in\Omega_{\text{WTG}}} \mathrm{Cost}^{\text{WTG}} x_i^{\text{WTG}} \tag{14}$$

2)Operation Cost

$$\mathrm{Cost}_{\text{sub}}^{\text{ope}} = D\delta^{\text{sub}} \sum_{t\in T} \sum_{i\in\Omega_{\text{sub}}} P_{i,t}^{\text{sub}} x_i^{\text{sub}} \tag{15}$$

$$\mathrm{Cost}_{\text{line}}^{\text{ope}} = \delta^{\text{line}} \sum_{ij\in\Omega_{\text{line}}} Lo_{ij} x_{ij}^{\text{line}} \tag{16}$$

$$\mathrm{Cost}_{\text{WTGshed}}^{\text{ope}} = D\delta^{\text{WTGshed}} \sum_{t\in T} \sum_{i\in\Omega_{\text{WTG}}} (P_{i,t}^{\text{WTG\_Pre}} - P_{i,t}^{\text{WTG}}) \tag{17}$$

$$\mathrm{Cost}_{\mathrm{EVloadshed}}^{\mathrm{ope}} = D\delta^{\mathrm{EVloadshed}} \sum_{t\in T} \sum_{i\in\Omega_{\mathrm{pile}}} (P_{i,t}^{\mathrm{EVload\_Pre}} - P_{i,t}^{\mathrm{EVload}}) \quad (18)$$

$$\mathrm{Cost}_{\mathrm{loss}}^{\mathrm{ope}} = D\delta^{\mathrm{loss}} \sum_{t\in T} \sum_{ij\in\Omega_{\mathrm{LINE}}} (I_{ij,t})^2 r_{ij} \quad (19)$$

where t indicates the time; i is the grid bus. The variable $\mathrm{Cost}^{\mathrm{inv}}$ and $\mathrm{Cost}^{\mathrm{ope}}$ indicate investment cost and operation cost respectively. The subscript of sub, line, EVCS, WTG, chargingpile, WTGshed, EVloadshed and loss represent the substation, line, EVCS, WTG, charging pile, the curtailment of WTG output, the curtailment of EV load and the network loss respectively. For example, $\mathrm{Cost}_{\mathrm{sub}}^{\mathrm{inv}}$ indicates the investment cost of the substation. m represents the life cycle of the device. DR is the discount rate. $\mathrm{Cost}^{\mathrm{sub\_new}}$ and $\mathrm{Cost}^{\mathrm{sub\_ext}}$ are the cost of new construction and expanding of the substation. Lo_{ij} is the line length. $\mathrm{Cost}^{\mathrm{pile}}$ is the price per charging pile. $\mathrm{Cost}^{\mathrm{line}}$ is the price per unit length of the line. s is the EVCS charger number. $\mathrm{Cost}_i^{\mathrm{EVCS\_fix}}$ and $\mathrm{Cost}_i^{\mathrm{EVCS\_var}}$ are the fix price and variable price of each EVCS charger. D represents the number of days in the whole year. $\delta^{\mathrm{WTGshed}}$ and $\delta^{\mathrm{EVloadshed}}$ are the shedding price. δ^{sub} and δ^{line} represent the maintenance price. δ^{loss} is the price of the network loss. $P_{i,t}^{\mathrm{sub}}$ is the generated power. $P_{i,t}^{\mathrm{WTG}}$ and $P_{i,t}^{\mathrm{WTG\_Pre}}$ are the actual power and forecasted power of WTG, and so do $P_{i,t}^{\mathrm{EVload\_Pre}}$ and $P_{i,t}^{\mathrm{EVload}}$. x is the investment decision variable. Ω indicates the set of the locating buses of the corresponding network device. The subscript LINE means the whole buses in the grid.

B. Constraints

1) Investment Constraints

$$\sum_{y\in\Gamma^{\mathrm{EVCS}}} x_{i,y}^{\mathrm{EVCS}} = 1 \quad (20)$$

$$0 \le \sum_{y\in\Gamma^{\mathrm{sub}}} x_{i,y}^{\mathrm{sub}} \le 1 \quad (21)$$

$$0 \le x_i^{\mathrm{pile}} \le \overline{N}_i^{\mathrm{pile}} \quad (22)$$

$$0 \le x_i^{\mathrm{WTG}} \le \overline{N}_i^{\mathrm{WTG}} \quad (23)$$

$$0 \le Cap^{\mathrm{WTG}} \sum_{i\in\Psi_{\mathrm{WTG}}} x_i^{\mathrm{WTG}} \le L^{\mathrm{WTG}} \sum_{i\in\Psi_{\mathrm{B\_N}}} Load_i \quad (24)$$

where Γ^{EVCS} is the EVCS planning scheme. Γ^{sub} means the planning scheme for the substation. Equation (22) and (23) indicate the investment limit for the charging pile and WTG. Equation (24) means the integrated penetration constraint for WTG.

2)Security Constraint

To linearize the power flow model, define:

$$U_{i,t}^* = (U_{i,t})^2 \quad (25)$$

$$I_{ij,t}^* = (I_{ij,t})^2 \quad (26)$$

Then the security constraint is as follows:

$$(\underline{U})^2 \le U_{i,t}^* \le (\overline{U})^2 \quad (27)$$

$$0 \le I_{ij,t}^* \le (\overline{I_{ij}})^2 \quad (28)$$

where $\underline{U}$ and $\overline{U}$ are the bus voltage limits. $\overline{I_{ij}}$ is the line current limit.

2)Power Balance Constraint

$$\sum_{k\in\pi(i)} (P_{ki,t} - r_{ki} I_{ki,t}^*) - \sum_{j\in\varsigma(i)} P_{ki,t} + P_{i,t}^{\mathrm{sub}} + P_{i,t}^{\mathrm{WTG}} = P_{i,t}^{\mathrm{Load}} + P_{i,t}^{\mathrm{EVCS}} + P_{i,t}^{\mathrm{EVload}} \quad (29)$$

$$\sum_{k\in\pi(i)} (Q_{ki,t} - x_{ki} I_{ki,t}^*) - \sum_{j\in\varsigma(i)} P_{ki,t} + Q_{i,t}^{\mathrm{sub}} + Q_{i,t}^{\mathrm{WTG}} = Q_{i,t}^{\mathrm{Load}} \quad (30)$$

$$U_{j,t}^* \le U_{i,t}^* - 2(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}) + I_{ij,t}^*[(r_{ij})^2 + (x_{ij})^2] + M(1 - x_{ij}^{\mathrm{L}}) \quad (31)$$

$$U_{j,t}^* \ge U_{i,t}^* - 2(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}) + I_{ij,t}^*[(r_{ij})^2 + (x_{ij})^2] - M(1 - x_{ij}^{\mathrm{L}}) \quad (32)$$

$$I_{ij,t}^* U_{i,t}^* = (P_{ij,t})^2 + (Q_{ij,t})^2 \quad (33)$$

Equation (33) can be transferred as follows:

$$\left\| \begin{matrix} 2P_{s,ij,t} \\ 2Q_{s,ij,t} \\ I_{s,ij,t}^* - U_{s,i,t}^* \end{matrix} \right\|_2 \le I_{s,ij,t}^* + U_{s,i,t}^* \quad (34)$$

3)WTG Operation Constraint

$$0 \le P_{i,t}^{\mathrm{WTG}} \le P_{i,t}^{\mathrm{WTG,Pre}} \quad (35)$$

$$Q_{i,t}^{\mathrm{WTG}} = \tan[\cos^{-1}(\rho^{\mathrm{WTG}})] P_{i,t}^{\mathrm{WTG}} \quad (36)$$

where ρ^{WTG} is the power factor of WTG.

4)Uncertain Charging Load Constraint

$$0 \le P_{i,t}^{\mathrm{EVload}} \le P_{i,t}^{\mathrm{EVload\_Pre}} \quad (37)$$

5)Generating Power Constraint

$$\underline{P_i^{\mathrm{sub}}} \le P_{i,t}^{\mathrm{sub}} \le \overline{P_i^{\mathrm{sub}}} \quad (38)$$

$$\underline{Q_i^{\mathrm{sub}}} \le Q_{i,t}^{\mathrm{sub}} \le \overline{Q_i^{\mathrm{sub}}} \quad (39)$$

where $\underline{P_i^{\mathrm{sub}}}$, $\overline{P_i^{\mathrm{sub}}}$, $\underline{Q_i^{\mathrm{sub}}}$ and $\overline{Q_i^{\mathrm{sub}}}$ are the upper and lower limits for the active power and reactive power of the generator, respectively.

6)Radial Operation Constraint

$$N_{\mathrm{LINE}} = N_{\mathrm{B\_N}} - N_{\mathrm{sub}}(x_i^{\mathrm{sub}}) \quad (40)$$

$$\sum_{j\in\varsigma(i)} P'_{s,ki,t} - \sum_{k\in\pi(i)} (P'_{s,ki,t} - r_{ki} I^{*'}_{s,ki,t}) = \varepsilon \tag{41}$$

$$\sum_{j\in\varsigma(i)} Q'_{s,ki,t} - \sum_{k\in\pi(i)} (Q'_{s,ki,t} - x_{ki} I^{*'}_{s,ki,t}) = \varepsilon \tag{42}$$

$$U^{*'}_{s,j,t} \le U^{*'}_{s,i,t} - 2(r_{ij}P'_{s,ij,t} + x_{ij}Q'_{s,ij,t}) + I^{*'}_{s,i,t}[(r_{ij})^2 + (x_{ij})^2] + M(1 - x^{\mathrm{L}}_{ij}) \tag{43}$$

$$U^{*'}_{s,j,t} \ge U^{*'}_{s,i,t} - 2(r_{ij}P'_{s,ij,t} + x_{ij}Q'_{s,ij,t}) + I^{*'}_{s,i,t}[(r_{ij})^2 + (x_{ij})^2] - M(1 - x^{\mathrm{L}}_{ij}) \tag{44}$$

$$\left\| \begin{matrix} 2P'_{s,ij,t} \\ 2Q'_{s,ij,t} \\ I^{*'}_{s,ij,t} - U^{*'}_{s,j,t} \end{matrix} \right\|_2 \le I^{*'}_{s,ij,t} + U^{*'}_{s,j,t} \tag{45}$$

where $N_{\mathrm{B\_N}}$, N_{LINE} and N_{sub} are the number of buses, lines and substations respectively. ε is a small value representing the small load.

IV. Case Studies

A. Test System

In this section, the 54-node distribution network and the Sioux—Falls transportation network are adopted as the test system, which is shown in Fig. 1 and Fig. 2. The upgrading scheme for substation 52 and 53 is shown in Table I. The expanding scheme for substation 54 is shown in Table II. The candidate EVCS planning scheme can be seen from [11]. The discount rate is set to 0.15. Line investment price per unit length in a year is set to 1×10^6 yuan and the operation price is 4500 yuan. Other investment and operation parameters can refer to [12]. The variable σ is set to 0.2.

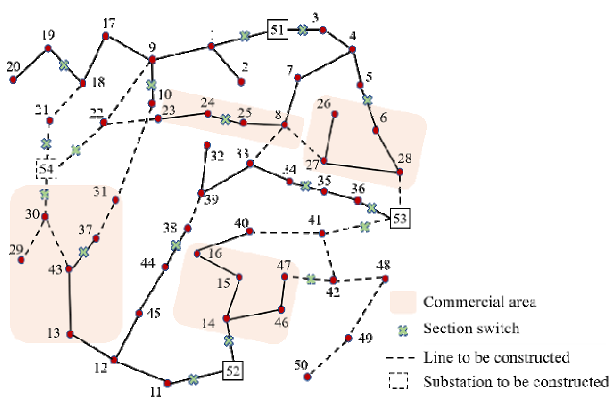

Fig.1. The 54-node distribution network.

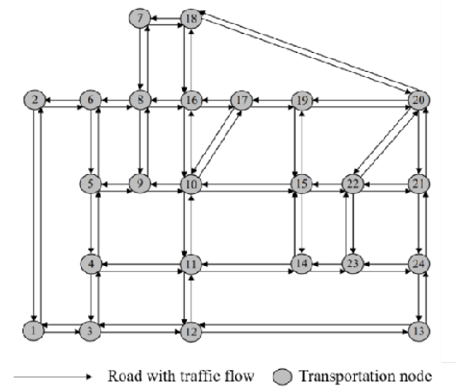

Fig. 2. The Sioux—Falls transportation network.

TABLE I. The upgrading scheme for substation 52 and 53

	Expanded Capacity/MW	Cost/(10^7 yuan)
Scheme a	6	6
Scheme b	10	9

TABLE II. The constructing scheme for substation 54

	Expanded Capacity/MW	Cost/(10^7 yuan)
Scheme a	3	3
Scheme b	6	6
Scheme c	10	9

B. Results

To verify the effectiveness of the RO planning method proposed in this paper, the deterministic method is adopted to perform the contrastive analysis. The optimization method is shown in Table III and Fig. 3. Define the following scenario to perform the contrastive analysis.

Case 1: Optimal planning based the robust optimization

Case 2: Optimal planning based the deterministic optimization

TABLE III. Planning results based on deterministic optimization and DRO methods ignoring reliability benefit

	Investment Scheme						Cost ($\times10^8$ yuan)
	Sub	Line		EVCS	WTG		
Case 1	52(1,0)	54-21	53-41	Scheme 15	20(13)	42(0)	2.5796
	53(0,1)	54-22	47-42		25(5)	6(0)	
	54(0,1,0)	29-30	42-48		39(6)	26(9)	
		30-54	48-49		16(10)	31(16)	
		37-31	49-50		50(9)	30(10)	
					13(9)	27(5)	
					28(0)	47(2)	
					14(0)		
Case 2	52(0,0)	22-23	41-42	Scheme 4	20(11)	42(0)	1.9873
	53(0,1)	54-21	42-48		25(9)	6(0)	
	54(1,0,0)	54-30	48-49		39(10)	26(7)	
		30-29	49-50		16(14)	31(13)	
		53-41	37-31		50(5)	30(0)	
					13(13)	27(7)	
					28(0)	47(5)	
					14(0)		

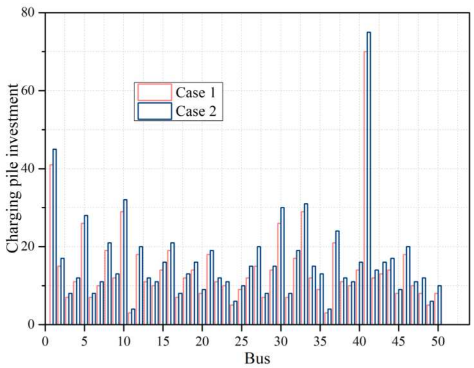

Fig. 3. The investment planning of charging pile

From the data above, it can be seen that the planning scheme based on RO method is more conservative than the one based on the deterministic method. First, compared to Case 2, the upgraded degree of substation 52 and 52 are increased in Case1. This is because the load burden of these two substations is increases, which can be seen from the planning scheme of the line. For the EVCS planning scheme, although the cost of Scheme 15 is larger than Scheme 4, its capability of undertaking the increasing EV charging load is better than Scheme 4, which means the planning scheme based on RO method is more suitable to the distribution network with many uncertain factors. For the WTG planning, it is found that compared to the deterministic optimization, WTG investment based on RO is mainly focused on those located at the end of the branch. This means the load located at the end of the feeder is more easily to be curtailed and providing DG supply is a good way to increase their power quality. And for the charging pile planning, it is easily to see that the charging pile investment based on RO is larger than the deterministic optimization, which is because the uncertainty of charging demand is considered during the planning process based on RO. Applying the above planning scheme based on Case 1 and Case 2 and perform reliability evaluation, it is found the reliability level based on Case 1 is higher the Case 2, which means the planning scheme based on Case 1 is more able to ensure the reliable operation of the distribution network. To analysis the economic of the planning scheme, the specific cost data is listed as Table IV shows.

TABLE IV. Costs based on deterministic optimization and DRO methods ignoring reliability benefit

	Costs/(×10^8yuan)					
	Investment	Line Operation	Generation	Network Loss	Wind Curtailment	EV Charging Load Curtailment
Case 1	1.0313	0.0139	1.5069	0.0180	0	0.0095
Case 2	0.4387	0.0109	1.5071	0.0191	0	0.0115

From the table above, we can see that the investment cost based on RO is larger than the one based on deterministic method while the generation cost, network loss and EV charging load curtailment cost are smaller than the deterministic method. This is because the planning scheme by RO is more conservative, thus the operation is more optimized. It means the RO model can not only effectively reduce the generating power, but also avoid the load curtailment, which reduces the annual operation cost.

V. Conclusion

Considering the uncertainty of EV charging demand and WTG output, a robust joint planning model of EV charging infrastructures and distribution networks is proposed in this paper. The case studies show that the planning scheme based on RO method is more able to ensure the reliable operation of the distribution network. And as it is optimized in the worst scenario, the planning scheme based on RO method can not only effectively reduce the generating power, but also avoid the load curtailment, which reduces the annual operation cost.

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