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# Stochastic Distribution Network Planning with Uncertain Renewable Energy Based on Credibility Assessment

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**Abstract.** Due to the uncertainty of renewable energy and complex construction of distribution network, the wind-solar power integrated distribution network is one of the most difficult optimization problems in operational planning of power system. This paper proposes a risk-based credibility assessment (RbCA) model for stochastic distribution network planning (SDNP) with wind-solar power penetration to obtain the optimal planning from the perspective of risk aversion. In the proposed model, the uncertain wind power and solar power are designed as credibility interval variables, and the operation risk of SDNP is measured by the credibility assessment of wind-solar power. In addition, in consideration that the SDNP is a constrained non-convex and multi-modal optimization problem, and the particle swarm optimization (PSO) is easily trapped into premature convergence in dealing with this kind of problems, a dynamic PSO with escaping prey (DPSOEP) has been developed to increase the diversity of the population and then obtain the optimal planning of distribution network. Simulation results obtained based on the modified IEEE 33 nodes distribution system show that the proposed model and algorithm are reasonable and effectiveness in dealing with the SDNP with uncertain wind-solar power penetration, considering the integration of various inequality and equality constraints. Introduction

## 1. Introduction

The reliable and economic planning of distribution network plays an important role for distribution system, which aims to minimize the total operational cost while satisfying various inequality and equality constraints. In the last few years, because of the non-polluting, inexhaustible and available planet-wide, a large number of distributed wind power and solar power have been integrated into distribution network to reduce pollution emission and mitigate the fossil energy crisis [1]. However, the wind-solar power is innately uncertain which brings more uncertainties for distribution network operation. In addition, it is argued that the forecasting error of wind-solar power cannot be avoided even using the best forecasting method [2]. Therefore, the wind-solar power integrated distribution network becomes a stochastic planning problem, and the high penetration leads to high risk for



distribution network planning. Moreover, studies have indicated that inappropriate selection of size of wind-solar power may lead to greater operation cost than that without its integration [3].

In recent years, various methodologies are available in the literature for stochastic distribution network planning (SDNP) considering uncertain wind-solar power penetration. These methodologies include analytical method, fuzzy method, stochastic method, interval method and robust method. In [4], an analytical method is developed to calculate the optimal size of distributed generation by minimizing power losses. In order to minimize power loss as well as improve voltage stability, Moradi and Abedini presented a combination of genetic algorithm and particle swarm optimization for optimal sizing of renewable energy [5]. However, the analytical method and interval method cannot well reflect the uncertain characteristic of the renewable energy, and the fuzzy method is subjected to strong subjectiveness in some cases and cannot adjust well to the actual needs [6]. As for the robust method, it may face the challenges of proving the worst case scenario and obtainment of a trackable model [7,8].

The above literature review indicates that although methods for SDNP have been developed, there are still some limitations that need to be fulfilled. Most of the models existed concentrate on the expected cost and the risk level rarely are evaluated. In addition, some of the models need to repeated sample the wind-solar power or calculate a multi-objective optimization. Moreover, the optimization algorithms employed are easily fall into local optimal solution in dealing with non-convex and multi-modal SDNP. In view of this, this paper proposes risk-based credibility assessment (RbCA) model for SDNP, to assess the uncertain wind-solar power from the perspective of balancing the risk and expected cost. In addition, a dynamic particle swarm optimization (DPSO) has been developed to increase the diversity of the optimization population and then obtain the optimal penetration level of solar power.

## 2. Risk-based credibility assessment model for stochastic distribution network planning

The objective of the stochastic distribution network planning (SDNP) aims to maximize the investment benefit under uncertain wind-solar power penetration, while making full use of the available wind-solar power resource in the scheduling period as much as possible. Thus, the objective function of SDNP is defined by the investment benefit of wind-solar power for electric power generation over one year, which is the difference between the annual revenue and annual cost of wind-solar power. The annual revenue  $C_R$  includes the benefits of selling electricity and the policy subsidy of wind-solar power, while the annual cost  $C_I$  includes the installation costs, operation and maintenance costs and the fuel costs of wind-solar power.

$$\begin{aligned} \max \quad & F = C_R - C_I \\ \text{s.t.} \quad & g(X, U, P_W, P_S) = 0, \quad h(X, U, P_W, P_S) > 0 \end{aligned} \quad (1)$$

where

$$\begin{aligned} C_R &= 8760 \left( (C_W^{\text{OG}} + C_W^{\text{GS}}) P_W + (C_S^{\text{OG}} + C_S^{\text{GS}}) P_S \right) \\ C_I &= 8760 \left( C_W^{\text{MC}} P_W + C_S^{\text{MC}} P_S \right) + C_W^{\text{FI}} P_W + C_S^{\text{FI}} P_S \end{aligned} \quad (2)$$

$C_W^{\text{OG}}$  and  $C_W^{\text{GS}}$  are respectively the on-grid price and the government subsidy of wind power,  $C_S^{\text{OG}}$  and  $C_S^{\text{GS}}$  are respectively the on-grid price and the government subsidy of solar power,  $C_W^{\text{MC}}$  and  $C_W^{\text{FI}}$  are respectively the maintenance cost and fixed investment cost of wind power,  $C_S^{\text{MC}}$  and  $C_S^{\text{FI}}$  are respectively the maintenance cost and fixed investment cost of solar power,  $X$  and  $U$  represent the vectors of state variables and decision variables, respectively,  $P_W$  and  $P_S$  are the power generated by the wind turbine and solar array, respectively, and  $g$  and  $h$  represent the equality and inequality constraints, respectively.

To ensure security operation within allowable power limits, the solution must satisfy the branch power flow, voltage limits and power limits constraints. For a radial distribution network with  $n+1$  nodes and  $n$  branches, the power flow formulation can be formulated as

$$\begin{aligned} P_{D,i} + V_i \sum V_k (G_{jk} \cos \theta_{jk} + B_{jk} \sin \theta_{jk}) &= P_{W,i} + P_{S,i} \\ Q_{D,i} + V_i \sum V_k (G_{jk} \sin \theta_{jk} - B_{jk} \cos \theta_{jk}) &= Q_{W,i} + Q_{S,i} \end{aligned} \quad (3)$$

where  $P_{D,i}$  and  $Q_{D,i}$  denote the active and reactive load demand of node  $i$ , respectively.

The voltage of each node should be kept within the safe operating limits:

$$V_{\min} \leq V_i \leq V_{\max} \quad (4)$$

where  $V_{\min}$  and  $V_{\max}$  are the minimum and maximum permissible voltage limits, respectively.

### 2.1. Credibility assessment of wind-solar power

Firstly, define the deviation values of wind power  $\varepsilon_W$  and solar power  $\varepsilon_S$

$$\varepsilon_W = \frac{P_W - P_{WP}}{P_{WP}}, \quad \varepsilon_S = \frac{P_S - P_{SP}}{P_{SP}} \quad (5)$$

where  $P_{WP}$  and  $P_{SP}$  represent the wind power and solar power when  $v = \mu_W$  and  $s = \mu_S$ , respectively.

Then construct the membership functions of deviation values according to Cauchy distribution [9]:

$$\Phi_W = \begin{cases} \frac{1}{1 + \omega(\varepsilon_W/E_{W+})}, & \text{if } \varepsilon_W \geq 0 \\ \frac{1}{1 + \omega(\varepsilon_W/E_{W-})}, & \text{otherwise} \end{cases}, \quad \Phi_S = \begin{cases} \frac{1}{1 + \omega(\varepsilon_S/E_{S+})}, & \text{if } \varepsilon_S \geq 0 \\ \frac{1}{1 + \omega(\varepsilon_S/E_{S-})}, & \text{otherwise} \end{cases} \quad (6)$$

where  $\omega$  represents the weighting coefficient,  $E_{W+}$  denotes the distribution probability of wind power when  $P_W > P_{WP}$ , and  $E_{W-}$  denotes the distribution probability of wind power when  $P_W < P_{WP}$ ,  $E_{S+}$  denotes the distribution probability of solar power when  $P_S > P_{SP}$ , and  $E_{S-}$  denotes the distribution probability of solar power when  $P_S < P_{SP}$ .

Finally, the credibility assessments of wind power and solar are:

$$v(P_W) = \begin{cases} 1 - \frac{1}{2[1 + \omega(\varepsilon_W/E_{W+})^2]}, & \text{if } \varepsilon_W \geq 0 \\ \frac{1}{2[1 + \omega(\varepsilon_W/E_{W-})^2]}, & \text{otherwise} \end{cases} \quad (7)$$

$$v(P_S) = \begin{cases} 1 - \frac{1}{2[1 + \omega(\varepsilon_S/E_{S+})^2]}, & \text{if } \varepsilon_S \geq 0 \\ \frac{1}{2[1 + \omega(\varepsilon_S/E_{S-})^2]}, & \text{otherwise} \end{cases} \quad (8)$$

### 2.2. Risk-based credibility assessment model for SDNP

In RbCA, the wind power and solar power are designed as credibility interval variables, and the risk is measured by their credibility assessment while the profit is measured by difference between the annual revenue and annual cost of wind-solar power shown by Equation (1).

The detailed descriptions of RbCA are given as follows.

Note that forecasting errors of wind speed and solar radiation both follow the Gaussian distribution, the confidence intervals of wind speed and solar radiation under a given  $\alpha$  can be obtained by:

$$P\left(\left|\frac{v - \mu_W}{\sigma_W}\right| > Z_{\frac{\alpha}{2}}\right) = \alpha \Rightarrow P\left(-Z_{1-\frac{\alpha}{2}} \leq \frac{v - \mu_W}{\sigma_W} \leq Z_{1-\frac{\alpha}{2}}\right) = 1 - \alpha \quad (9)$$

and the confidence interval of wind speed is:

$$\frac{v - \mu_W}{\sigma_W} \in [-Z_{1-\frac{\alpha}{2}}, Z_{1-\frac{\alpha}{2}}] \Rightarrow v \in [\mu_W - Z_{1-\frac{\alpha}{2}}\sigma_W, \mu_W + Z_{1-\frac{\alpha}{2}}\sigma_W] \quad (10)$$

And the confidence interval of solar radiation can be obtained similar to that of the wind speed.

Here, the objective function is defined as the economic profit which is the product of investment benefit and credibility assessment under renewable energy integrated. Thus, the RbCA model for SDNP is formulated as follows:

$$\begin{aligned} \max \quad & E = v(P_W)(P_S)(C_R - C_I) \\ \text{s.t.} \quad & g(X, U, P_W, P_S) = 0, \quad h(X, U, P_W, P_S) > 0 \end{aligned} \quad (11)$$

### 3. Simulation studies

The proposed RbCA is tested on the modified IEEE 33 nodes power system with wind power and solar power integrated. As for the wind power, the corresponding parameters  $v_{ci}=4$  m/s,  $v_{co}=20$  m/s,  $v_{ra}=12.5$  m/s,  $P_{ra}=2$  MW,  $\mu_w=9.37$  m/s,  $\sigma_w=0.3\mu_w$ . For solar power, the parameters  $\mu_s=226$  W/m<sup>2</sup>,  $\sigma_s=0.3\sigma_s$ ,  $k_s=150$  W/m<sup>2</sup>,  $G_{SE}=1000$  W/m<sup>2</sup>,  $P_{SE}=1$  MW,  $\omega=2.33$ . The locations of wind turbine and solar array are set to be on nodes 25 and 29 according to the power loss sensitivity factor method [10]. In this paper, the confidence level of wind speed is set to 95%, then  $\alpha=0.05$ ,  $Z_{1-\alpha/2}=1.96$  [11].

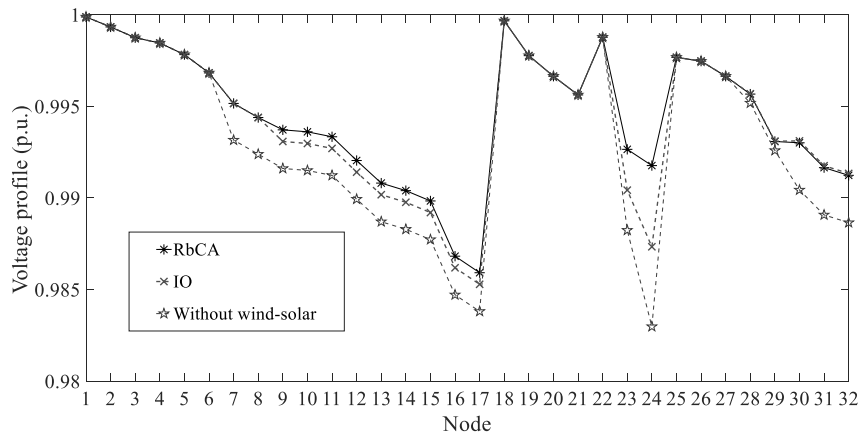
As the dynamic PSO with escaping prey (DPSOEP) is a well-known meta-heuristic method to obtain the optimal solution in dealing with non-convex and multi-modal optimization problems [12], without loss of generality, we thus employ this method for solving RbCA.

In order to validate the effectiveness of RbCA, the interval optimization (IO) model is used for comparison. In IO, the optimization model is the same as Equation (11) except that the credibility assessment is not considered. The optimal economic profit, investment benefit, credibility assessment, wind power and solar power obtained based on RbCA and IO are given by Table 1. Note that the economic profit provided in Table 1 is the product of investment benefit and credibility assessment. From the table, we can see that the economic profit obtained by RbCA is positive, which means that the penetration of wind and solar power can make an economic profit for SDNP under risk aversion. Additionally, the allowable wind power and solar power are not maximized generation limitations. The reason is that a high penetration of wind-solar power corresponds to a low credibility assessment, which brings high operation risk for SDNP. Therefore, we can conclude that the RbCA can reach the optimal trade-off between the profit and risk by balancing investment benefit and credibility assessment.

**Table 1.** Comparison of simulation results obtained based on RbCA and IO.

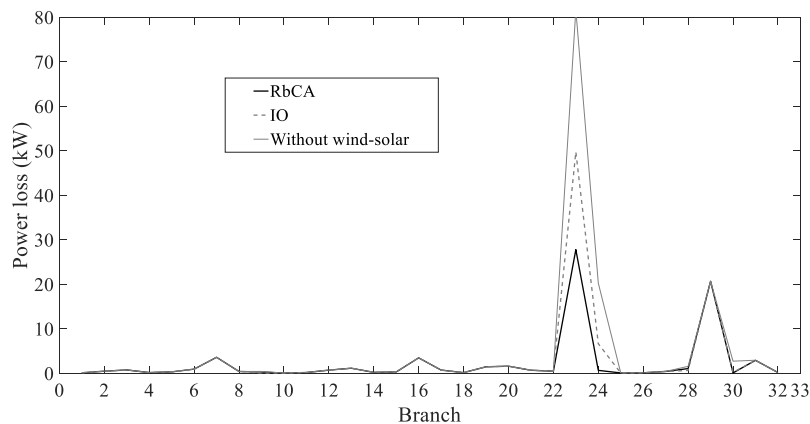
| Model | Economic profit | Investment benefit | Credibility assessment (wind/solar) | Wind power (MW) | Solar power (MW) |
|-------|-----------------|--------------------|-------------------------------------|-----------------|------------------|
| RbCA  | 2.1927          | 2.4893             | (0.8808, 1)                         | 0.3365          | 0.0057           |
| IO    | 1.2918          | 2.9352             | (0.4401, 1)                         | 0.4150          | 0.0035           |

Though the optimal investment benefit obtained by IO is higher than that of RbCA, the credibility assessment of IO is much lower than that of RbCA. It means that the solution obtained by IO will bring a high risk for SDNP. In consideration of investment benefit and credibility assessment, the economic profit obtained by RbCA is 2.1927, which increases 69.74% than that of IO. In addition, we can see that the credibility assessment of solar power equals to 1, which means that the risk of solar power can be ignored under a low penetration level. Figure 1 depicts voltage profiles of RbCA and IO for each node. The results show that the wind-solar power penetration can improve voltage levels. Furthermore, based on the RbCA, the voltage levels at most of the nodes for SDNP have improved. It is also clear that the voltage levels obtained by RbCA are more stability than that of IO with uncertain wind-solar power penetration.



**Figure 1.** Voltage profile of the modified IEEE 33 nodes.

The power losses are shown by Figure 2. From the figure, it is clearly seen that the solution obtained by RbCA can reduce power losses. More precisely, the optimal total power losses obtained by RbCA and IO are 67.17 kW and 94.37 kW, respectively, which are both lower than 149.25 kW obtained without wind-solar power penetration. This means that wind-solar power penetration can reduce power losses of SDNP. On the other hand, a higher penetration level of wind power (obtained by IO) cannot obtain a smaller power loss. Thus, it is necessary to control the penetration level of renewable energy from the perspective of power loss and voltage level.



**Figure 2.** Voltage distribution of each node for the modified IEEE 33 nodes.

In addition, the locations of wind turbine and solar array are discussed in this subsection. It should be mentioned that the nodes selected in this paper are based on the power loss sensitivity factor method. The optimal economic profit, investment benefit, credibility assessment, total power loss and maximum voltage deviation considering different locations are given by Table 2. From the table, we can clearly see that the power loss sensitivity factor method is efficient for selecting the install locations of wind turbine and solar array. On the other hand, the locations of wind turbine and solar array play an important role for SDNP in terms of improving voltage level and reducing power loss.

**Table 2.** Comparison of simulation results obtained based on RbCA and IO.

| Node(wind/solar) | Economic profit | Investment benefit | Credibility assessment (wind/solar) | Power loss (kW) | Voltage deviation (kW) |
|------------------|-----------------|--------------------|-------------------------------------|-----------------|------------------------|
| (25, 29)         | 2.1927          | 2.4893             | (0.8808, 1)                         | 67.1672         | 0.0138                 |

|              |        |        |             |          |        |
|--------------|--------|--------|-------------|----------|--------|
| (32, 16)[5]  | 0.8260 | 0.8127 | (0.9827, 1) | 146.3287 | 0.0170 |
| (2, 6)[13]   | 0.1518 | 0.1529 | (0.9928, 1) | 145.9274 | 0.0169 |
| (24, 14)[13] | 1.8497 | 2.0351 | (0.9089, 1) | 92.0600  | 0.1455 |

#### 4. Conclusion

In this paper, a risk based credibility assessment (RbCA) model for the planning of stochastic distribution network with uncertain renewable energy penetration is proposed. In RbCA, the wind power and solar power are designed as the credibility interval variables, and the investment benefit is defined as the difference between the annual revenue and annual cost of wind-solar power while the risk is defined by the credibility assessment of wind-solar power. In comparison with the interval optimization model, the proposed RbCA can reach a trade-off penetration level of wind-solar power for SDNP between the investment benefit and operation risk. In addition, based on the RbCA, the voltage level and power loss have been improved. Moreover, the install locations of wind turbine and solar array should be considered in SDNP from the perspective of reducing power loss and improving voltage level.

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