# A Multi-Timing Source-Network-Load-Storage Coordinated Planning Method for Box-Type Substation-Based ADNs

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**Abstract**—A two-layer planning model for network-source coordination of active distribution networks considering power and load timing characteristics is proposed. The upper layer of the model is the planning layer, which makes decisions for online modification, selection, siting and capacity setting of distributed power sources and compensation capacitors to minimize the comprehensive cost. The lower layer of the model is the operation layer, which takes the annual operation cost, fast voltage stability, and customer satisfaction with power usage habits as the objectives, considers the volatility and uncertainty of distributed power sources and loads, establishes the timing model of the two, and comprehensively considers the output of distributed power sources, demand response, and compensating capacitor casting and cutting, also the intelligent adjustment of the box-type substation, to realize the economic dispatch of the active distribution network. The improved IEEE 33-node power distribution system is used to simulate the method of this paper, and the simulation results show that the network source coordination planning method proposed in this paper can effectively reduce the investment cost and operation cost of the active distribution network, and at the same time, it can effectively improve the efficiency of the grid operation and the penetration rate of distributed power sources.

**Keywords**—active distribution network; distributed power sources; timing characteristics; network source coordination planning

## 1. INTRODUCTION

With the increasing economic growth, the demand for electricity load continues to increase, and the distribution network bears most of the load demand, therefore, power companies need to invest a lot of money every year to upgrade the distribution network to meet the needs of load growth [1-2].

Experts have carried out in-depth studies on the planning and operation of distribution networks and achieved numerous research results. Literature [3] proposed traditional distribution network planning methods such as grid planning and reactive power compensation planning. With the development of active distribution networks, the traditional methods can no longer meet the planning needs of active distribution networks. Since active distribution grids can be actively regulated, the planning of active distribution grids covers both the planning and operation levels

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of distribution grids. At the planning level, the literature [4] takes into account the impact of DG access to the distribution network and proposes the method of DG siting and capacity setting and the method of network upgrading, respectively. At the operation level, the existing literature mainly focuses on the three aspects of DG output, reactive power compensation, and demand response [5-6], and develops efficient dispatch schemes to improve the network voltage level and smooth the main grid power output [7].

This paper proposes an active distribution network source coordination planning method considering the timing characteristics of power and load. A two-layer planning model is established by considering the timing characteristics of DG and load. The planning layer takes the minimization of integrated cost as the objective function, and the decision variables are line upgrading or not, and the siting and capacity setting of DG and compensation capacitors. In the operation layer, the objectives are minimizing the annual operation cost, optimizing the fast voltage stability index, and maximizing the customer's satisfaction with the electricity consumption habit, and the decision variables are the output of DG and the power factor adjustment of controllable DG, the switching of the compensation capacitor, the adjustment of transformer tap, and the node load adjustment coefficients. The binary and discrete integer variables in the planning layer are solved using the binary particle swarm algorithm and the improved particle swarm algorithm, respectively, and the operational layer is solved using the NSGA-II algorithm. The IEEE 33-node system is utilized as an example for simulation to verify the effectiveness of the algorithm proposed in this paper and to derive the optimal planning scheme.

## 2. TWO-TIER COORDINATED PLANNING MODEL

An active distribution network source coordination planning model that considers the timing characteristics of power sources and loads is developed and the model is divided into upper and lower layers. The upper layer is the planning layer, and the decision variables are the upgrading of the grid, the siting of distributed power sources (DGs) and capacitors, and capacity-setting. The lower layer is the operation layer, and the decision variables are the output of DG and the power factor adjustment factor of DG, the switching of compensation capacitors, the adjustment of transformer taps, and the nodal load adjustment factor in each timing scenario.

The two-tier coordinated planning model described in this paper can be represented as:

$$\begin{cases} F(x^{\text{plan}},x^{\text{oper}}) = \min(C^{\text{I}}+C^{\text{O}}) \\ s.t.\quad G(x^{\text{plan}}) \le 0 \\ \qquad H(x^{\text{plan}}) = 0 \\ f(x^{\text{oper}}) = \min(C^{\text{O}}) \\ s.t.\quad g(x^{\text{oper}}) \le 0 \\ \qquad h(x^{\text{oper}}) = 0 \end{cases} \tag{1}$$

$$\begin{aligned} x^{\text{plan}} = \{ & x_{ij}^{\text{Line}}, x_i^{\text{WTG}}, y_i^{\text{WTG}}, x_i^{\text{PVG}}, y_i^{\text{PVG}}, \\ & x_i^{\text{MTG}}, y_i^{\text{MTG}}, x_i^{\text{CB}}, y_i^{\text{CB}} \} \end{aligned} \tag{2}$$

$$\begin{aligned} x^{\text{oper}} = \{ & n_{i,s,t}^{\text{WTG}}, n_{i,s,t}^{\text{PVG}}, n_{i,s,t}^{\text{MTG}}, n_{i,s,t}^{\text{CB}}, \alpha_{i,s,t}^{\text{q,WTG}}, \\ & \alpha_{i,s,t}^{\text{q,PVG}}, \alpha_{i,s,t}^{\text{p,MTG}}, \alpha_{i,s,t}^{\text{q,MTG}}, T_{s,t}^{\text{gen}}, \lambda_{i,s,t} \} \end{aligned} \tag{3}$$

Where, $x_{ij}^{\text{Line}}$ , $x_i^{\text{WTG}}$ , $x_i^{\text{PVG}}$ , $x_i^{\text{MTG}}$ , $x_i^{\text{CB}}$ denote the decision variables of branch *ij* upgrading, whether node *i* installs WTG or not, whether node *i installs* PVG or not, whether node *i* installs MTG or not, whether node *i installs* CB or not, respectively, which are all 0-1 variables. $y_i^{\text{WTG}}$ , $y_i^{\text{PVG}}$ , $y_i^{\text{MTG}}$ , $y_i^{\text{CB}}$ denote the number of WTGs, PVGs, MTGs, and CBs installed at node *i,* respectively, all are shaping variables.

## 2.1 Planning level

*1) Objective function*

The objective function of the planning layer is to minimize the integrated cost.

$$F_1 = \min(C^{\text{I}} + C^{\text{O}}) \tag{4}$$

$$C^{\text{I,Line}} = \sum_{ij \in \Omega^{\text{Line}}} c^{\text{Line}} l_{ij} x_{ij}^{\text{Line}} \tag{5}$$

$$\begin{aligned} C^{\text{I,DG}} = & \sum_{i \in \Omega^{\text{WTG}}} c^{\text{WTG}} x_i^{\text{WTG}} y_i^{\text{WTG}} + \sum_{i \in \Omega^{\text{PVG}}} c^{\text{PVG}} x_i^{\text{PVG}} y_i^{\text{PVG}} \\ & + \sum_{i \in \Omega^{\text{MTG}}} c^{\text{MTG}} x_i^{\text{MTG}} y_i^{\text{MTG}} \end{aligned} \tag{6}$$

$$C^{\text{I,CB}} = \sum_{i \in \Omega^{\text{CB}}} c^{\text{CB}} x_i^{\text{CB}} y_i^{\text{CB}} \tag{7}$$

where $C^{\text{I}}$ denotes the investment cost and the superscripts Line, DG and CB denote line investment, DG investment and capacitor investment, respectively. $\Omega^{\text{Line}}$ , $\Omega^{\text{WTG}}$ , $\Omega^{\text{PVG}}$ , $\Omega^{\text{MTG}}$ , $\Omega^{\text{CB}}$ denote the line set, WTG alternative installation node, PVG alternative installation node, MTG alternative installation node, and capacitor alternative installation node, respectively. $c^{\text{Line}}$ , $c^{\text{WTG}}$ , $c^{\text{PVG}}$ , $c^{\text{MTG}}$ , $c^{\text{CB}}$ , and $l_{ij}$ denote the cost per unit length of line upgrade, cost per unit of WTG installation, cost per unit of PVG installation, cost per unit of MTG installation, cost per unit of CB installation, and length of branch *ij*, respectively.

*2).Constraints*

DG total installed node count limit:

$$\sum_{i \in \Omega^{\text{WTG}}} x_i^{\text{WTG}} + \sum_{i \in \Omega^{\text{PVG}}} x_i^{\text{PVG}} + \sum_{i \in \Omega^{\text{MTG}}} x_i^{\text{MTG}} \le N_{\max}^{\text{DG}} \tag{8}$$

CB total installed node count limit:

$$\sum_{i \in \Omega^{\text{CB}}} x_i^{\text{CB}} \le N_{\max}^{\text{CB}} \tag{9}$$

WTG, PVG, MTG, and CB installation quantity limits:

$$\begin{cases} y_i^{\mathrm{WTG}} \le y_{\max}^{\mathrm{WTG}} \\ y_i^{\mathrm{PVG}} \le y_{\max}^{\mathrm{PVG}} \\ y_i^{\mathrm{MTG}} \le y_{\max}^{\mathrm{MTG}} \\ y_i^{\mathrm{CB}} \le y_{\max}^{\mathrm{CB}} \end{cases} \tag{10}$$

### 2.2.Operational layer

*1).Objective function*

There are three objective functions at the operation level, which are $f_1$ operating cost, $f_2$ Fast voltage stability (FVS), and $f_3$ customer satisfaction with electricity usage habits.

(1) Running costs

The runtime layer objective function $f_1$ is the minimization of the runtime cost, i.e.

$$f_1 = \min C^o \tag{11}$$

(2) Voltage indicators

The Fast Voltage Stabilization (FVS) is used to calculate the voltage metric of the distribution network. The smaller the value of this indicator, the higher the system stability.

The branch *ij* denotes the branch with *i* as the first node and *j* as the last node, then the voltage stability index of the branch *ij* at time *t of* season *s* is as follows:

The voltage stability of each branch is calculated as shown in the following equation.

$$FVS_{ij,s,t} = \frac{4\left(R_{ij}^2 + X_{ij}^2\right)Q_{j,s,t}}{U_{j,s,t}^2 X_{ij}} \tag{12}$$

where $R_{ij}$ and $X_{ij}$ denote the resistance and reactance of the branch *ij*, respectively.

The maximum value of voltage stability of each branch is used to represent the voltage stability of the system. Therefore, the operation layer objective function $f_2$ is minimized for the system FVS.

$$f_2 = \min\left[\max\left(FVS_{ij,s,t}\right)\right] \tag{13}$$

## 3.SIMULATION ANALYSIS

### 3.1 Illustrative examples

In this paper, IEEE 33 node power distribution system is used for simulation. The topology of the system is shown in Fig. 1. In the figure, numbers with parentheses indicate branch numbers and numbers without parentheses indicate node numbers.

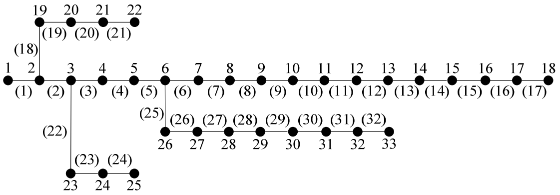

**Fig. 1.** Topological structure of IEEE 33-node system

The system parameters are set as follows:

In this example, nodes 2 to 18 are set as residential load nodes; nodes 26 to 33 are commercial load nodes; and nodes 19 to 25 are industrial load nodes. During the planning cycle, the system load growth is two times of the initial value. The model of the upgraded line is LGJ-240, and the unit impedance is 0.107+j0.405 Ω/km; the operating costs of WTG, PVG, and MTG are 0.5 Yuan/kWh, 0.5 Yuan/kWh, and 0.6 Yuan/kWh, respectively; the unit cost of wind and light discarded is 0.3 Yuan/kWh; the cost of line loss is 0.4 Yuan/kWh; the cost of purchasing electricity from the higher-level power grid is 0.4 Yuan/ kWh; the rated power factor of WTG and PVG is 0.85; the transformer tap has 9 adjustment stops, and the voltage can be adjusted within the range of 0.95pu~1.05pu; the residential load node is an adjustable load, and the value of load adjustment coefficient ranges from 0.85 to 1, with an adjustment cost of RMB 1/kWh; the capacity of the unit of WTG is 0.3MVA, with an investment cost of RMB 60,000 yuan. and the maximum number of accesses per node is 10; the capacity of unit PVG is 0.2MVA, the investment cost is 40,000 yuan, and the maximum number of accesses per node is 10; the capacity of unit MTG is 0.3MVA, the investment cost is 50,000 yuan, and the maximum number of accesses per node is 10; and the capacity of unit CB is 0.05Mvar, the investment cost is 0.7 million yuan, and the maximum number of accesses per node is 10 groups. The maximum number of accesses per node is 10 units. The upper and lower limits of node voltage are 0.93pu and 1.07pu respectively.

### 3.2 Simulation results

Since the decision variables in the upper layer of this paper are the siting of DGs and CBs with fixed capacity, to reduce the search space and improve the convergence speed, this paper first performs active and reactive access tests on the original IEEE 33-node system.

The simulation results of the method in this paper are shown in Tables 1 to 4.

**TABLE 1.** PLANNING SCHEME OF THE PROPOSED METHOD

| Planning program | Planning results |
|---|---|
| Line Upgrade | 1, 2, 5 |
| WTG site selection (number) | 26(1), 31(1) |
| PVG siting (number) | 6 (4), 31 (10) |
| MTG siting (number) | 8(1), 12(1) |
| CB sites (number) | 6(1), 7(7), 11(10), 12(7), 27(1), 31(7) |

**TABLE 2.** INVESTMENT COST OF THE PLANNING SCHEME

| Bus route investors /$10,000 | WTG investors /$10,000 | PVG investors /$10,000 | MTG investors /$10,000 | CB investors /$10,000 | Total investment /$10,000 |
|---|---|---|---|---|---|
| 79.08 | 12 | 56 | 10 | 23.1 | 180.18 |

**TABLE 3.** ANNUAL OPERATING COSTS OF THE PLANNING PROGRAM

| Net loss cost/$10,000 | Cost of purchasing electricity/$10,000 | WTG Running Costs/Million | PVG operating costs/million dollars | MTG operating costs/million dollars |
|---|---|---|---|---|
| 23.84 | 888.14 | 93.68 | 347.07 | 168.92 |

**TABLE 4.** OTHER INDEXES OF THE PLANNING SCHEME

| FVSI/pu | Customer satisfaction with electricity consumption habits/% |
|---|---|
| 0.5587 | 99.987 |

According to Table 1, it can be seen that the number of lines to be upgraded by the method of this paper are 1, 2 and 5, and the upgraded lines are characterized by being closer to the higher level of power supply, and therefore delivering more power and need to be upgraded.

## 4 CONCLUSION

In this paper, a two-layer planning model for active distribution network network source coordination considering power and load timing characteristics is developed, where the upper layer is solved by using a combination of BPSO and MPSO methods with the objective of integrated cost, and the lower layer is solved by the NSGA-II algorithm with the indicators of operating cost, FVSI and customer satisfaction with power usage habits. Based on the simulation results, the following conclusions can be obtained:

1. Reasonable access of distributed power supply helps to reduce distribution network loss and improve the voltage level of distribution network. However, too high penetration of distributed power supply access to the grid will cause the enhancement of distribution network losses and trigger the voltage overrun problem.

2. WTG has certain anti-peaking characteristics, and PVG's output characteristic curve and load characteristic curve match well, which can be used as the main form of distributed power supply access to the distribution network.

3. the method in this paper takes into account the DG access, CB casting and demand response, and develops a more reasonable distribution network planning program, and the proposed method has a certain guiding significance for distribution network planners.

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