Real-time coordination optimization method of active distribution network considering different stakeholders

Cheng Sun¹,²*, Shi Su¹

¹Electric Power Research Institute, Yunnan power Gird Co., Ltd., Kunming, Yunnan, 650217, China
²School of Electrical and Electronic Engineering, North China Electric Power University, Beijing 102206, China

*Corresponding author’s e-mail: suncheng0115@ncepu.edu.cn

Abstract. In order to reduce the impact of renewable energy output and load forecasting error on the network operation optimization and realize the mutual benefit and win-win situation of multiple stakeholders, a real-time coordination optimization method of active distribution network considering different stakeholders is proposed in this paper. Firstly, the daily real-time coordination and optimization framework of active distribution network is proposed. Then, the intraday real-time rolling two-level optimal scheduling model was solved by nonlinear particle swarm optimization and primal dual interior point method. The results of the calculation examples show that the proposed scheduling model and method can maximize the common interests of different subjects of the distribution network and flexible resources, so that the network can guarantee lower operating costs on the basis of safe operation.

1. Introduction
With the increasing penetration of distributed power (DG) in the distribution network and the rapid growth of demand side response loads, the traditional distribution network has evolved into an active distribution network (ADN) which includes wind-solar power, various DG and flexible loads. However, the operation and scheduling methods of traditional distribution network have been unable to meet the operational requirements of the current power system [1-3]. At the same time, it can not be used to coordinate the economic benefits of the distribution network and different parties on the user side. Renewable energy such as wind-solar energy has the characteristics of random, intermittent and fluctuating output, and its prediction has a certain error. After large-scale and distributed power supply is connected to the distribution network, problems such as large reverse power transmission power and difficult voltage control will occur [4-5]. As DG penetration continues to increase, these problems will worsen.

At present, scholars at home and abroad have conducted related studies from different perspectives on the operation optimization of ADN. Literature [6-7] considered controllable DG and flexible controllable load, and established a scheduling model with the minimum operating cost of ADN. Literature [8] takes the comprehensive operating cost of the whole distribution system in a certain period as the objective function for optimization. However, the above research did not consider the role of energy storage unit in ADN optimal scheduling. Literature [9] takes wind-solar renewable energy and maximizing operating benefits of active loads as coordination goals, and active loads take flexible resources on load side and electric vehicles with energy storage characteristics into account.
Literature [10-11] takes the minimum operating cost of ADN as the objective function to conduct global optimization scheduling for ADN. However, the above centralized scheduling method fails to reflect the respective demands of different interest subjects.

To sum up, this paper first proposes a real-time coordination optimization method of active distribution network considering different stakeholders. Firstly, the real-time hierarchical and hierarchical coordination optimization framework of active distribution network is proposed. In the intraday real-time stage, the upper and lower intraday optimization models are established. Then the model is solved and the effectiveness of the proposed model and method is verified.

2. Real-time coordination and optimization architecture of active distribution network

This paper mainly includes AND (upper layer) and flexible resource layer (lower layer) at the spatial level. The upper layer cannot directly dispatch the lower layer and uses price to guide in the electricity market environment. Days real-time phase respectively by ADN to minimize the cost and operation cost by the economic benefits of the flexible resources to maximize days inside the upper and lower level optimization model is established with the target, the upper consider the interests of the subject of active power distribution network, the optimization goal for ADN run to minimize the cost, the amount of optimized variables for various flexible resources and upper ADN lower market price; The lower level considers the main interests of each flexible resource, the optimization goal is to maximize the economic benefits of each flexible resource, and the optimization variable is the output scheduling value of each flexible resource. The upper layer guides the state of DG, energy storage and interruptible load of the lower layer through price optimization. In turn, the lower layer responds to the price optimization signal of the upper layer, adjusts its own output power, and returns the optimization results to the upper layer.

3. Real-time coordination optimization model of active distribution network

3.1 Upper-level optimization model

The objective function of the upper optimization model is shown as follows:

$$\min \Gamma = \sum_{n=1}^{N} (C_{DG} + C_{IL} + C_{grid})$$

(1)

1) **Purchase power from DG and reduce the cost of power output**

$$C_{DG} = \sum_{n=1}^{N} \left[ \rho_{DG}^L \cdot \Delta t \cdot P_{DG}^L + \rho_{DGcut}^L \cdot \Delta t \cdot (\overline{P}_{DG}^L - P_{DG}^L) \right]$$

(2)

$$P_{DG}^L \cdot \Delta t \cdot \rho_{DGcut}^L$$ is divided into the day-ahead planned active power output of DG in the t period of the n station and the actual active power output in the real-time stage; \( \rho_{DG}^L \) and \( \rho_{DGcut}^L \) are respectively the price of the upper layer purchasing 1kWh of electric energy from the n-th DG of the lower layer and the compensation price of the upper layer cutting 1kWh of electricity generation to the lower layer.

2) **The cost of purchasing electricity from the superior grid**

$$C_{grid} = \rho_{grid}^L \cdot \Delta t \cdot P_{grid}^L$$

(3)

3) **Demand side response costs**

$$C_{IL} = \sum_{i=1}^{N} \left[ \rho_{IL} \cdot \Delta t \cdot P_{IL}^L + \left( \rho_{sell}^L - \rho_{grid}^L \right) \cdot \Delta t \cdot \rho_{IL}^L \right]$$

(4)

\( P_{IL}^L \) is the active power value reduced by the user I in the time period t; \( \rho_{IL} \) is obtained for the reduction of 1kWh of electric power for the response of IL users as stipulated in the contract; \( \rho_{sell}^L \) is the TOU price sold by the distribution company to users.

1) Active power balance constraint:
\[ \sum_{n=1}^{N_{DG}} P_{DG,n} + \sum_{n=1}^{N_{BAT}} P_{BAT,n} + \sum_{n=1}^{N_{PV}} P_{PV,n} + P_{WT} + P_{grid} = P_{LOAD} \]  

\( P_{t}^{LOAD}, P_{t}^{PV}, P_{t}^{WT} \) are the short-term load forecast and wind-scene forecast values in period \( t \), respectively.

2) Flow constraint:

\[ P_{t} = U_{i} \sum_{j=1}^{N_{ILN}} (G_{ij} \cos \delta_{j} + B_{ij} \sin \delta_{j}) \]

\[ Q_{t} = U_{i} \sum_{j=1}^{N_{ILN}} (G_{ij} \sin \delta_{j} - B_{ij} \cos \delta_{j}) \]

3) Upper-level optimization of price constraints:

\[ \rho_{DG, min}^{DG} \leq \rho_{DG}^{DG} \leq \rho_{DG, max}^{DG} \]  

\[ \rho_{DGcut, min}^{DGcut} \leq \rho_{DGcut}^{DGcut} \leq \rho_{DGcut, max}^{DGcut} \]  

\[ \rho_{bid, min}^{bid} \leq \rho_{bid}^{bid} \leq \rho_{bid, max}^{bid} \]

4) DG run constraints:

\[ P_{DG, i, min} \cdot U_{i,j} \leq P_{DG, i,t} \leq P_{DG, i, max} \cdot U_{i,j} \]

\[ P_{DG, i,t} - P_{DG, i,t-1} \leq R_{DG, i} \]

\( P_{DG, i, min}, P_{DG, i, max} \) is the output limit of the DG of the \( i \)th platform, \( R_{DG, i} \) is the climbing limit of DG of Platform \( i \).

5) Energy storage unit operating constraints:

\[ P_{BAT, k, min}^{BAT} \leq P_{BAT}^{k,t} \leq P_{BAT, k, max}^{BAT} \]  

\[ SOC_{j, min} \leq SOC_{j,init} + \frac{P_{BAT, j}}{Q_{BAT}} \cdot \Delta t \leq SOC_{j, max} \]

6) Market power purchase constraints:

\[ P_{grid}^{grid} \leq P_{grid, max}^{grid} \]

3.2 Lower-level optimization model

According to the transaction price optimized by the upper layer, the lower layer takes the maximum economic benefit of the flexible resource layer as the optimization objective, and its specific objective function of economic benefit is:

\[ \max f_{i} = \sum_{n=1}^{N_{DG}} \left[ C_{DG} + C_{IL} - C^{cons} \right] \]

\[ C_{DG} = \sum_{n=1}^{N_{DG}} \Delta t \cdot \left[ \rho_{DG}^{DG} \cdot P_{DG}^{DG} + \rho_{DGcut}^{DGcut} \cdot (\overline{P}_{DG} - P_{DG}^{DG}) \right] \]

\[ C_{IL} = \sum_{n=1}^{N_{IL}} \rho_{bid}^{bid} \cdot P_{IL}^{bid} \cdot \Delta t \]

\( C^{cons}_{DG} \) is the cost of electricity generation for DG. Constraint conditions include DG mentioned above, operational constraints of energy storage, and power constraints of IL load.

4. Solution algorithm

The upper layer is a nonlinear programming problem, which requires high computational speed, so the primal dual interior point method is used to solve the real-time optimization model. The lower model is a linearized model, which is solved by CPLEX. A circular iteration is carried out between the upper
and lower levels. When the error between the various flexible resource outputs optimized by the upper model and the results optimized by the lower model is less than the set value, the optimization is stopped and the optimal flexible resource outputs and electricity price results are output.

5. The example analysis

5.1 The example simulation

The topology of the example system is shown in Fig. 1. Wind power and photovoltaic power are installed at nodes 32 and 13 respectively, and their output is shown in Fig. 3. Two sets of fuel cell packs are installed at nodes 7, 17 and 30 respectively, each with a full power of 300KW; two sets of micro gas turbine sets with a full power of 390KW; energy storage and dispatching units with a total capacity of 1800KVA and a maximum charge/discharge power of 200KW; Interruptible loads are provided at nodes 16 and 23, with maximum load reduction of 350kW per group.

The DERs parameters in the optimization model in this paper are as follows: \( P_{n,\text{min}} \), \( D_{n,\text{max}} \) are zero, \( P_{n,\text{max}} \) takes the full power of each DG, The upper and lower limits of SOC power of the energy storage unit are 0.9 and 0.2 respectively. The initial SOC is 0.7, and the charge and discharge efficiency is 0.95. The initial population number is set as 300 in the particle swarm optimization algorithm, and the maximum and minimum weight coefficients of 300 generation operation are 0.9 and 0.3 respectively. The learning factor \( c_1 \) and \( c_2 \) are set as 2. The predicted results of photoelectricity and load of stroke in this example are shown in Figure 2.

5.2 Optimization results and analysis

The optimization results of daily output of each part, daily output of each DG and daily output of each flexible resource are obtained through simulation examples. The load gaps mentioned in this paper are as follows: \( \Delta P_{L,t} = P_{t,\text{load}} - P_{t,\text{WT}} - P_{t,\text{PV}} - P_{t,\text{grid}} \).
The optimization results are shown in Figure 3 and 4. In Fig. 3, DG operator will reduce the output during the load trough and when the renewable energy output is strong to prevent the voltage from exceeding the upper limit. For energy storage operators, charging in the period of low load and discharging in the period of high load can effectively realize the role of peak clipping and valley filling, and ensure the economic and safe operation of the power grid. During peak electricity consumption, scheduling of demand response load can improve the voltage level of system nodes, reduce network loss, and meet the requirements of low carbon and environmental protection. In Figure 4, for the distributed power supply, in the load trough period, the power purchase price is low and the reduction compensation price is high, so as to facilitate the reduction of the output of the distributed power supply. In the load peak period, the power purchase price is high and the reduction compensation price is low, so as to facilitate the increase of the output of the distributed power supply to meet the load demand. For the demand response load, load reduction is carried out at 17-22, and the interrupt compensation price at this time is also high: therefore, the optimization result of price is consistent with the scheduling result of flexible resources, which proves the correctness of the model method in this paper.

The optimization results of the proposed method are compared with those of the two scheduling modes of no optimal scheduling and single-layer centralized scheduling, as shown in Table 1:

| Tab.1 Comparison of optimization results of different scheduling modes |
|---------------------------------------------------------------|
| **scheduling**                                                                                      | **Only the FR power is optimized** | **The optimization method in this paper** |
| Power system cost (Yuan) | 51231.77 | 50894.01 |
| Network loss (kW)        | 4504.841 | 4134.674 |
| Revenue from FR (yuan)   | 8255.91  | 8923.56  |
| Min system voltage (kV)  | 9.380963 | 9.561567 |

6. conclusions

Numerical example results show that the presented scheduling model and the method can effectively coordinate the economic benefit of distribution companies as well as flexible resources, realize the maximization of their common interests, at the same time can enhance the operation of the power distribution network level, improve their ability to given and distributed energy management, under the power grid based on the safe operation of the guarantee lower running costs.

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