Hierarchical control strategy based on bidding mechanism in active distribution network

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Abstract: With the penetration of intermittent energy rising and controllable objects increasing in active distribution network (ADN), centralised control is difficult to guarantee the optimally real-time status of the grid and distributed control cannot consider all controllable objects together. Therefore, hierarchical control architecture is proposed. This paper divides ADN into some regions and focuses on regions’ cooperative control strategy. Based on the global optimisation result, regions optimise with each other in short-time scales. According to the indicator of feeder control error, the control mechanism that reacts to real-time power fluctuation is established. Further, this paper puts forward ADN region cooperative control strategy based on bidding mechanism. Communication mechanism based on blackboard system is used to avoid complex communication networks. The effectiveness and validity of ADN region cooperative control strategy is verified by the simulation of study case.

1 Introduction

In recent years, it puts forward new requirements for the operation and management of distribution network (DN) because of the high penetration of renewable energy such as photovoltaic (PV) and wind power. To make full use of the advantages and overcome the problems they bring, a new control mode should be introduced and applied to adapting to the high penetration of distributed energy resources (DERs). ADN, which is characterised by high penetration of DERs and high control requirements, has been generally accepted as an important development mode for smart grid [1].

Traditional DN always uses centralised control mode which schedules with 24 or 96 points [2]. However, the speed of centralised control mode is difficult to meet the real-time requirement due to the unpredictability and rapid change of PV and wind power. So decentralised control mode [3] attracts wide attention due to its smaller control range, less control variable and better real-time performance. However, decentralised control mode only considers its own optimisation and cannot consider the whole operation state of ADN. It is difficult to achieve the whole optimisation of ADN.

In this paper, a hierarchical mode, which includes global layer and autonomous layer [4], is proposed to cope with technical challenges for DN with high penetration of DERs. This mode has the integrity of centralised control mode and flexible features of decentralised control mode. In this mode, global optimisation schedules regions’ target curve then regions follow the target curve. Region is autonomous to restrain the intermittent power fluctuation in real time. The authors of [5] present hierarchical control can give full play to its autonomy compared with centralised control. Especially in the transient process and communication network failure state, regional autonomous control can maintain stable operation of the system. In addition, hierarchical control can control the system operation from the global level and achieve the stability and economy of the whole network compared with decentralised control.

In the hierarchical mode, how to coordinate the regions’ global optimisation goal is difficult. In [6], global optimisation sets 24 h target curve and feeders, which act as lower control units, conduct real-time local re-optimisation. The authors of [7] schedule the DN layer on the global level. The micro-grid layer optimises the exchange power between micro-grids to get optimal benefits. However, due to the unpredictability and rapid change of PV and wind power, above research lacks the re-coordination between regions so it is difficult to realise the optimal operation of the ADN in real time. At present, the research about global optimal dispatching is abundant. For example, the authors of [8] propose an algorithm based on intelligent single particle optimiser. In [8], DERs and sectionalising switches are taken into consideration together to schedule in next 24 h.

To realise ADN control target in different time scales, a new region cooperative control method is needed to ensure the real-time optimisation of ADN. This paper divides ADN into regions and focuses on region cooperative control strategy. Based on the global optimisation result, regions optimise with each other in short-time scales. The indicator of feeder control error in [9] is used to establish ADN region’s autonomous control mode. For further optimisation of the ADN real-time operation, this paper puts forward ADN region cooperative control strategy based on bidding mechanism. Communication mechanism based on blackboard system is used to avoid complex communication networks. The effectiveness and validity of this strategy is verified by the simulation of study case.

2 ADN hierarchical control strategy

2.1 Hierarchical control structure

To deal with the communication pressure and real-time control requirement of large numbers of DERs, this paper proposes a hierarchical control structure, including:

(i) Global optimisation layer: Based on intermittent energy and load forecast results, distribution management system (DMS) arranges and optimises ADN’s operation on the global level. Global optimisation sets DER output curve and lower-layer optimisation goal, such as regional exchange power, in next 24 h. The global optimisation considers the whole information of
ADN and the calculation period is too long to consider the real-time fluctuations of intermittent energy and load.

(ii) **Regional autonomous control layer**: This layer is controlled by regional control unit which receives optimisation targets from DMS. Regional control unit will respond to the real-time power fluctuation of the ADN and coordinate DERs to realise region internal stability and reduce the influence between different regions.

The autonomous region can divide according to the following principles: All DERs, between one sectionalising switch and the end of feeder or between two different sectionalising switches, form an autonomous region. This partition method is well adapted to the characteristics of DN because the regional scale will not change when the sectionalising switch changes status. It owns high flexibility and adaptability. In addition, the sectionalising switches usually configure as measurement points in DN so the value of regional exchange power can be collected in real time. It is convenient for ADN to carry out the whole state monitoring and control (Fig. 1).

### 2.2 Regional autonomous control strategy

The research results of global optimisation are abundant and this paper focuses on region control. The indicator of feeder control error (FCE) proposed by [9] is used to form the regional objective function of region \( i \)

\[
\Delta P_{\text{FCE,}i} = k_i \times \Delta P_j + \Delta P_{\text{region,}i} = 0 \quad (1)
\]

where \( k_i \) is the power coordinative coefficient of region \( i \); \( \Delta P_j \) is the deviation between feeder actual exchange power and its optimisation target; \( \Delta P_{\text{region,}i} \) is the deviation between actual regional exchange power of region \( i \) and its optimisation target. The detailed description of (1) and following derived content can be found in [10].

According to (1), when there is \( \Delta P \) power fluctuation, it can be classified as the next two cases:

(i) **\( \Delta P \) occurs in the region \( j \)**: When the \( \Delta P \) occurs in the region \( j \), DERs in region \( j \) will adjust their power output to maintain the regional exchange power. How to allocate the \( \Delta P \) depends on the distribution coefficient. The operation state of all regions, including feeder exchange power, will not change and they still follow the target value.

(ii) **\( \Delta P \) occurs outside of the regions**: When the \( \Delta P \) occurs outside of the regions, the power fluctuation is allocated by the substation bus and regions together with the ratio of \( 1/(1 + \sum_{j \in G} k_j) \) and \( k_i/(1 + \sum_{j \in N} k_j) \). We can obtain the equations as follows:

\[
\Delta P_i = \Delta P_j/1 + \sum_{j \in G} k_j \quad (2)
\]

\[
\Delta P_{\text{region,}k} = -k_i \times \Delta P_j/(1 + \sum_{j \in N \cap G} k_j) \quad (k \in N, k \notin G) \quad (3)
\]

(iii) where \( N \) is the collection of all autonomous regions.

If one region cannot complete its optimisation target, the unfinished target will be undertaken by other regions in accordance with the regional coordinative coefficient. Assuming the collection of regions, which cannot complete their optimisation target, is \( G \). The deviation of feeder exchange power can be written as

\[
\Delta P_i = \left( \Delta P_j + \sum_{j \in G} \Delta P_{\text{region,}j} \right)/(1 + \sum_{j \in N \cap G} k_j) \quad (4)
\]

Other regions’ deviation of regional exchange power is given by

\[
\Delta P_{\text{region,}k} = -k_i \times \left( \Delta P_j + \sum_{j \in G} \Delta P_{\text{region,}j} \right)/1 + \sum_{j \in N \cap G} k_j \quad (k \in N, k \notin G) \quad (5)
\]

The power fluctuation undertaken by one region will be allocated to DERs in this region in accordance with the distribution coefficient

\[
\Delta P_{\text{DER,}m} = \alpha_{\text{DER,}m} \times \Delta P_{\text{region,}k} \left( \sum_{m} \alpha_{\text{DER,}m} = 1 \right) \quad (6)
\]

### 2.3 Analysis of DER deviation caused by FCE control

There are different kinds of load and intermittent energy sources in different regions of ADN. In addition, there is characteristic difference between different kind of loads, such as the resident load and industrial load. Therefore, it can be assumed that there is no correlation between the power fluctuations in different nodes. Then, according to the principle of FCE, each power fluctuation may cause changes in DERs. DERs can be divided into three operation states based on the deviation between current power output and target value.

(i) The first state is optimal state (\( S_o \)) and it represents current power output equals to target value.

(ii) The second state is positive deviation state (\( S_p \)) and it presents current power output is greater than target value.

(iii) The third state is negative deviation state (\( S_n \)) and it presents current power output is less than target value.

The energy storage system (ESS) is taken as an example. Its power output is affected by the state of charge (SOC) so following plan may fail if the power output continues to deviate from the target value. Therefore, optimisation results in the long-time scale may be affected if the regional optimisation just tracks global optimisation target. That may lead to a larger deviation from the optimal state.

As shown in Fig. 2, it is assumed that ESS in region 1 and region 2 is in positive deviation state. Micro turbine (MT) in region 3 is in

![Fig. 1 Hierarchical control structure of ADN](image-url)
negative deviation state. ESS in region 4 is in optimal state. PV and wind turbine (WT) are renewable energy and regional strategy does not control them.

DERs’ state in Fig. 2 can be represented by hollow circle as shown in Fig. 3. If there is a power fluctuation $\Delta P > 0$ outside of regions, DERs in regions 1–4 will shift to positive state based on (2) and (3). This state can be represented by solid circle as shown in Fig. 3a. In Fig. 3a, ESSs are gradually deviated from their own target value. At this moment, if regional coordinative coefficient of regions 1, 2 and 4 is reduced and regional coordinative coefficient of region 3 is added, power fluctuation caused by $\Delta P$ will be mainly undertaken by region 3. As shown in Fig. 3b, MT’s power output is closer to the target value and the deviation between other ESSs’ power output and target value is reduced too. To improve ADN operation and make DERs run more reasonable, following sections will introduce region cooperative control strategy based on bidding mechanism.

3 Region cooperative control strategy based on bidding mechanism

3.1 Application of bidding mechanism

According to the above analysis, fixed regional coordinative coefficient in FCE control will lead to sub-optimal state of DERs. Nevertheless, by setting the regional coordinative coefficient reasonably, ADN can achieve the optimal state in real-time based on global optimisation result. So this paper puts forward a region cooperative control strategy based on bidding mechanism on the basis of the proposed FCE control method [11–13]. There are three entities in bidding mechanism:

(i) **Bidding platform**: It summarises all kinds of bidding information and prepares trading plans. In this paper, DMS is used as the bidding platform, and it is considered that the bidding information from regional control units is true.

(ii) **Bidder**: It provides bidding information to bid. In this paper, each region is a bidder. The specific bid price is decided by the operation state of the region, and they bid for the real-time power fluctuation caused by intermittent energy and load to reduce the deviation from the target value.

(iii) **Successful bidder**: It should complete the contract. In this paper, regional coordinative coefficient of successful bidder will be modified in real-time based on bidding result.

3.2 Multi-factor evaluation mechanism

When multiple regions participate in bidding, it is necessary to evaluate the bid information provided by each region and select the bidder who is in line with the optimisation direction. Therefore, this paper selects three factors [14] that affect the direction of optimisation. The first is cost factor that evaluate economy in bidding. The second is deviation tolerance factor that evaluate the impact extent of current DERs’ status to subsequent operation. The third is optimal deviation factor that evaluate the deviation between DERs’ power output and target value.

(i) **Cost factor $c$**: Cost factor represents the cost of DERs undergoing power fluctuation. Its value is mainly based on the cost of various DERs and power generation. The range is [0,1].

(ii) **Deviation tolerance factor $e$**: At present, there are many types of DER in ADN, such as ESS and micro-turbine. Operating characteristics of different DERs are different. ESS is constrained by the SOC and the deviation from the target value may cause the subsequent plan cannot be completed. Therefore, deviation tolerance factor of ESS is small. MT can maintain the operation through the external fuel supply. It can be considered that the tolerance factor is big.

(iii) **Optimal deviation factor $a$**: The optimal deviation factor is obtained from the ratio of DER output deviation to the installed capacity. The concrete expression is given as

$$a = \frac{(P_t - P_{t, opt})}{P_{rated}}$$  \hspace{1cm} (7)

(iv) Where $a_t$ is the optimal deviation factor at time $t$; $P_t$ is the power output of DER at time $t$; $P_{t, opt}$ is the optimised target value in time interval $t$; $P_{rated}$ is the rated power of DER. This factor indicates the deviation of the DER operation state from the planned curve.

Each regional control unit will provide three factors in the power fluctuation bidding. The weights of three factors are given in each optimisation period. The concrete expression is given as

$$y = \begin{cases} a_1(1-c) + a_2e - a_3a_t, & \Delta P > 0 \\ a_1c + a_2e + a_3a_t, & \Delta P < 0 \end{cases}$$  \hspace{1cm} (8)

where $\Delta P$ is the value of power fluctuation; $a_1- a_3$ are weights, $a_1 + a_2 + a_3 = 1$. Different weights can achieve different emphasis. If $a_1$ is bigger, cost is the main consideration in regional real-time optimisation. If $a_2$ is larger, it is more inclined to the DER with higher deviation tolerance.

3.3 Communication mechanism based on blackboard system

To reduce the communication pressure of the system, original communication channel between DMS and regional control units is used to build the communication mechanism based on blackboard system [14]. DMS serves as the ‘blackboard’ and provides memory space to regional control units exchanging information. Each regional control unit serves as a ‘knowledge source’ and
provides its own bidding information. Each regional control unit combines its own information with other units’ information listed in ‘blackboard’. Then, it dynamically adjusts the regional coordinative coefficient. The concrete mechanism is shown in Fig. 4.

3.4 Method and process of regional coordinative coefficient updating

Above analysis shows that the regional control unit as a knowledge source provides DERs’ factors and other related data in this region. In this paper, feeder exchange power with external power grid is a bidder too. In the first step, intra-region power fluctuation will be undertaken by DERs in this region through adjusting distribution coefficient based on bidding information in this region. In the second step, extra-region power fluctuation will be undertaken by all DERs through adjusting distribution coefficient and regional coordinative coefficient based on all bidding information. The detailed algorithm flow is shown in Fig. 5 and regional coordinative coefficient is set to non-negative.

If all DERs reach the output limit, external power grid will bid to win all the power fluctuation.

4 Case study

Based on the case in [15], one feeder with partial expansion is used to verify the strategy proposed in this paper. The topological connection is shown in Fig. 6. There are four autonomous regions in this case and the external network is equivalent to infinite power source. DlgSILENT15.0 software was used to simulate the control strategy.

Global optimisation sets 15 min as a period so there are 96 periods in 1 day. In order to prove the effectiveness of control strategy in ADN, one period is selected to analyse it. The basic information shows in Section 8, Appendix 1.

The factors of different types of DER are shown in Table 1. Optimal deviation factor is calculated based on current DER output and the target value. ESS only shifts the energy usage time, so the cost factor is small. However, its output is limited by the SOC, deviation tolerance factor is small too. MT as a peak support unit cost is relatively big, and fossil fuels ensure that MT is less affected by previous output. Feeder exchange power with external power grid is the most stable and it has moderate cost and unaffected output ability.

4.1 Simulation results of region cooperative control strategy

Taking the cost as the primary object and the weight is, respectively, $a_1 = 0.6$, $a_2 = 0.2$, $a_3 = 0.2$. The simulation result of feeder exchange power is shown in Fig. 7. (The simulation results of regions are shown in Section 9, Appendix 2.) Taking the curve of feeder exchange power as an example, we can see that curve after control is closer to the target value than without control. Most power fluctuation in the first 300 s is undertaken by DERs so the feeder exchange power coincides with the target value. After 300 s, external power grid gradually undertakes the power fluctuation outside of the regions which causes the deviation of the feeder exchange power from target value. Exchange power fluctuations of four regions are reduced to some extent so the whole power grid is closer to the global target value.

### Table 1 Reference value of DG factors

| Object                     | Cost factor | Deviation tolerance factor |
|----------------------------|-------------|----------------------------|
| ESS                        | 0.3         | 0.3                        |
| MT                         | 0.6         | 0.7                        |
| Feeder exchange power      | 0.5         | 0.9                        |
(i) The bidding results of intra-region power fluctuation: This case has four regions and region 4 has two DERs. The bidding result of power fluctuation occurs in region 4 is shown in Fig. 8. Positive power fluctuations are undertaken by ESS4 and negative power fluctuation is undertaken by MT. The reason is that positive power fluctuations need to increase the DER output and ESS cost factor is smaller. Negative power fluctuation needs to reduce the DER output and MT cost factor is bigger. Thus, MT reduces the power to save more cost.

(ii) The bidding results of extra-region power fluctuation: After the bidding of intra-region power fluctuation, the bidding result of extra-region power fluctuation is shown in Fig. 9. Under this group of evaluation weight, extra-region power fluctuation is mainly undertaken by MT and feeder exchange power with external power grid. The reason is that the extra-region power fluctuation is negative and weight is partial to cost factor. The cost factor of MT and feeder exchange power is bigger so they undertake the negative power fluctuation.

4.2 Comparison of different evaluation weights

With different evaluation weights, different types of DER will undertake different power fluctuation. When the evaluation weights are set to $a_1 = 0.1$, $a_2 = 0.1$, $a_3 = 0.8$, optimal deviation factor will be considered as a priority. Under this circumstance, the bidding results of intra-region and extra-region are shown in Figs. 10 and 11.

Due to the deviation caused by undertaking intra-region power fluctuation, each ESS undertakes the extra-region power fluctuation partially. Positive power fluctuation is still undertaken by ESS2.

5 Conclusion

(i) ADN hierarchical and regional control strategy can adapt to the volatility of intermittent energy. Based on the global optimisation result, regions optimise with each other in short-time scales. The effectiveness and validity of this strategy is verified by the simulation of study case.

(ii) This paper puts forward region cooperative control strategy based on bidding mechanism and communication mechanism based on blackboard system to achieve optimally real-time status. It is important to study ADN hierarchical control method and this strategy provides a new conception to improve DN operation.
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8 Appendix 1

The power fluctuation, generated by outside of four regions in the study case, is identified as the extra-region power fluctuation. The intra- and extra-region power fluctuations relative to forecast value in Tables 2–4 are shown in Fig. 12. Appendix 2

Table 3 Active power forecast of load

| Load          | P/MW | Load          | P/MW |
|---------------|------|---------------|------|
| A1            | 0.143| A14           | 0.284|
| A2            | 0.187| A15           | 0.081|
| A3            | 0.055| A17           | 0.066|
| A4            | 0.21  | A18           | 0.069|
| A5            | 0.077| A19           | 0.065|
| A6            | 0.067| A20           | 0.126|
| A7            | 0.07  | A21           | 0.097|
| A9            | 0.07  | PV1           | 0.151|
| A10           | 0.089| PV2           | 0.140|
| A11           | 0.114| WT            | 0.487|
| A12           | 0.137|              |      |
| A13           | 0.072|              |      |

Table 4 Target value of global optimisation

| Object          | Target value, MW | Coordinative coefficient |
|-----------------|------------------|--------------------------|
| feeder exchange power | 0.510            |                         |
| region 1        | 0.111            | 0.253                    |
| region 2        | 0.212            | 0.249                    |
| region 3        | 0.217            | 0.249                    |
| region 4        | –0.638           | 0.249                    |
| ESS1            | 0.097            |                         |
| ESS2            | 0.065            |                         |
| ESS3            | 0.129            |                         |
| ESS4            | 0.021            |                         |
| MT              | 0.2              |                         |

Table 2 Distribution energy resources configuration

| Type  | Node | Capacity |
|-------|------|----------|
| ESS1  | A6   | 250 kWh  |
| ESS2  | A10  | 250 kWh  |
| ESS3  | A12  | 250 kWh  |
| ESS4  | A19  | 250 kWh  |
| MT    | A20  | 300 kW   |
| PV1   | A6   | 500 kW   |
| PV2   | A14  | 500 kW   |
| WT    | A21  | 500*2 kW |

**“*2”** represents that there are two 500kW WTs

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Comparison of regions 1–4 exchange power before and after optimisation is shown in Figs. 13–16. Regions 1 and 3 do not undertake any extra-region power fluctuation so regional exchange power is exactly same as the global optimisation target value. Regions 2 and 4 undertake part of extra-region power fluctuation so there is deviation of regional exchange power from the target value. However, compared with the uncontrolled results, the power deviation is reduced.