Research on Transaction Clearing Method for Power Distribution Network Considering Reactive Power Support Ability of Renewable Energy

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Abstract. In order to solve the transaction clearing problem caused by the insufficient reactive power support ability of renewable energy, the reactive power regulation characteristics of renewable energy are studied and a power distribution network transaction clearing method considering renewable energy reactive power support ability is proposed. Wind power, photovoltaic and other renewable energy sources are generally connected to the power grid through power electronic equipment. Within the capacity control range, there are two adopted control modes including constant voltage and constant reactive power. According to the operation needs of power distribution network, a transaction clearing model aiming at the lowest power energy purchase cost is proposed. A transaction clearing method based on reactive power relaxation is proposed to improve the solving efficiency. Finally, a case study based on the REDS-32 buses system shows that the transaction clearing method can effectively consider the reactive power support ability of renewable energy sources, which could ensure that the transaction clearing results are close to the actual operation requirements and avoid the problem of bus voltage overruns affecting the safe operation of power distribution network.

1. Introduction

With the rapid development of wind power, photovoltaic and other renewable energy, a large number of renewable energy sources are connected to the power distribution network, which makes the operation and control of power distribution network more flexible and also provides the possibility of power market transaction for the different power sources in power distribution network. In recent years, the transaction market clearing mechanism and optimal dispatching method of distribution network have become an important research topic in this field.

The traditional market transaction clearing model of power distribution network mainly refers to the power market transaction experience of power transmission network, in which the bus voltage constraint and reactive power support ability of power sources are always ignored [1-2]. Considering the imbalance of the three phases in power distribution network, the three phases model is adopted in some power distribution network transaction clearing models to improve the availability of the transaction clearing model [3-4]. The ref. [5] takes the volatility of renewable energy generation output into consideration and proposes a power distribution network market optimization decision method based on the robust dispatching method. The ref. [6-7] studies the operation characteristics of distributed power sources and proposes a power market transaction clearing model for multi-type distributed power sources.
It could be seen that the current transaction clearing method of distribution network still continues the traditional power market transaction mode of transmission network. The basic idea is to regard the voltage of each bus in the distribution network as the rated value without considering the limitation of reactive power support ability of different power sources. In the traditional transmission network, the power sources is mainly thermal power and hydropower with large capacity and strong reactive power regulation ability, so the above assumptions can generally be met [8]. However, in the distribution network, the reactive power regulation capacity of renewable energy such as wind power and photovoltaic is limited and the voltage level of the distribution network must be considered.

To this end, this paper will research the transaction clearing method of distribution network with renewable energy reactive power ability. Firstly, the operation characteristics of renewable energy will be introduced with emphasis on the reactive power regulation ability of renewable energy source. Then, the transaction clearing model of distribution network market is constructed by considering the transaction operation objectives and system security constraints comprehensively. Finally, a case study based on REDS-32 buses system is used to verify the validity of the proposed method.

2. Operation characteristics analysis of renewable energy

2.1. Typical structure
As shown in fig. 1, although wind power, photovoltaic and other renewable energy power sources have different energy forms, they have the same power structure, which could be divided into power generation part and power conversion part [9]. Power generation part is the equipment collection that converts the primary energy such as wind and light into electric power energy. Wind power and photovoltaic have different power generation structures. However, they all preferentially convert primary energy such as wind and light into direct current energy in general. Power conversion part is to further convert the direct current energy through the power electronic devices for rectifier and inverter into AC electric power energy in line with the requirements of the distribution network voltage and frequency and transmit it to the distribution system.

![Figure 1. Renewable energy equipment structure](image)

2.2. Analysis of reactive power regulation characteristics
It can be seen from the above structural features that although there are many types of renewable energy, its operating characteristics are mainly related to the control strategy of its power conversion part. According to different control characteristics, renewable energy can be divided into two types: constant reactive power control and constant voltage control. Its operation characteristics can be expressed as:

\[
P^{RE}_{E2} + Q^{RE}_{E2} \leq S^{RE}_{E2}
\]

\[
Q^{RE} = Q^{S}_{set}
\]

\[
V^{RE} = V^{S}_{set}
\]

\[
P_{min}^{RE} \leq P^{RE} \leq P_{max}^{RE}
\]

\[
Q_{min}^{RE} \leq Q^{RE} \leq Q_{max}^{RE}
\]

where \( P^{RE} \) and \( Q^{RE} \) respectively represents the active power output and reactive power output of renewable energy power source. \( S^{RE} \) is the capacity of the renewable energy source. \( Q^{S}_{set} \) and \( V^{S}_{set} \) is respectively the given reactive power under constant reactive power mode and the target voltage under
the constant voltage control mode. $P_{RE, \text{max}}$ and $P_{RE, \text{min}}$ are the maximum and minimum active power output. $Q_{RE, \text{max}}$ and $Q_{RE, \text{min}}$ are the maximum and minimum reactive power output.

3. Power distribution network transaction clearing method

3.1. Optimization objective
The goal of distribution network market transaction is to satisfy the power demand of distribution network users with the lowest power purchase cost on the basis of ensuring the safe and stable operation of distribution network. Considering that the reactive power market has not yet been established in China and the reactive auxiliary service provided by power supply still adopts the administrative compensation mechanism, the active power cost is mainly considered in this paper. The optimization objective can be expressed as:

$$\text{Min} \sum_{i=1}^{NT} \sum_{r=1}^{NRE} P_{re}^{RE} \Delta T + \sum_{i=1}^{NT} p_{bb}^{BB} P_{bb,t}^{BB} \Delta T$$

(6)

where Min indicates that the optimization problem is a minimization optimization model. $NT$ is the optimization period number and $\Delta T$ is the corresponding time interval. $NRE$ is the number of renewable energy power sources in the power distribution network. $P_{re}^{RE}$ is the declared price of renewable energy source $re$. $P_{re,t}^{RE}$ is the active power output transaction clearing value of renewable energy $re$ at the time interval $t$. $p_{bb}^{BB}$ is the power price at the distribution network root node and is the power exchanged at the root node.

3.2. Constraints
There are two kinds of trading constraints in distribution network market, namely, distribution network operation constraints and renewable energy operation characteristics constraints.

(1) distribution network operation constraints
The distribution network operation constraints that need to be considered include power balance constraint, distribution network transfer characteristic constraint, distribution network transmission ability constraint and bus voltage constraint. The traditional distribution network transfer characteristics constraint, which is based on Newton-Rafson power flow, will introduce the positive cosine optimization, which causes the above clear model to be high in nonlinear and difficult to solve. To this end, the distflow power flow constraint is introduced in this paper [10]. The distribution network operation constraints can be expressed as:

$$P_{b2,t}^B = P_{b1-b2,t}^{Lin} - P_{b1-b2,t}^{Los} - \sum_{b2-b \in b2} P_{b1-b,t}^{Lin}$$

(7)

$$Q_{b2,t}^B = Q_{b1-b2,t}^{Lin} - Q_{b1-b2,t}^{Los} - \sum_{b2-b \in b2} Q_{b1-b2,t}^{Lin}$$

(8)

$$V_{b1,b2,t}^{2B} = V_{b1,t}^{2B} + V_{b2,t}^{2B} - 2V_{b1,t}^{B} V_{b2,t}^{B} (r_{b1-b2,t} P_{b1-b2,t}^{Lin} + x_{b1-b2,t} Q_{b1-b2,t}^{Lin}) + (r_{b1-b2,t}^2 + x_{b1-b2,t}^2)(P_{b1-b2,t}^{Lin} + Q_{b1-b2,t}^{Lin})^2$$

(9)

$$V_{b1,b2,t}^{2L} = V_{b1,t}^{2L} + V_{b2,t}^{2L} - 2V_{b1,t}^{L} V_{b2,t}^{L} (P_{b1-b2,t}^{Lin} + Q_{b1-b2,t}^{Lin}) + (r_{b1-b2,t}^2 + x_{b1-b2,t}^2)(P_{b1-b2,t}^{Lin} + Q_{b1-b2,t}^{Lin})^2$$

(10)

$$P_{b1-b2,t}^{Lin} + Q_{b1-b2,t}^{Lin} \leq S_{b1-b2}$$

(11)

$$V_{b1,t}^{B,\text{Max}} \leq V_{b1,t}^{B} \leq V_{b1,t}^{B,\text{Min}}$$

(12)

$$V_{b1,b2,t}^{2} \leq V_{b1,b2,t}^{2B}$$

(13)

where $P_{b2,t}^B$ and $Q_{b2,t}^B$ respectively represents the demand of active load and reactive load of bus $b2$ at the time interval $t$. $P_{b1-b2,t}^{Lin}$ and $Q_{b1-b2,t}^{Lin}$ respectively represents the active power flow and the reactive...
power flow of the power line $b1-b2$ at the time interval $t$ from bus $b1$ to bus $b2$. $P_{\text{Los}}^{b1-b2,t}$ and $Q_{\text{Los}}^{b1-b2,t}$ respectively represents the active power loss and the reactive power loss of the power line $b1-b2$ at the time interval $t$. $b2-bi \in b2$ represents the power line set which is connected to bus $b2$ except power line $b1-b2$. $V_{b1,t}^B$ and $V_{b2,t}^B$ are the voltage amplitudes of bus $b1$ and bus $b2$. $r_{b1-b2}$ and $x_{b1-b2}$ are respectively the resistance and reactance of power line $b1-b2$. $S_{b1-b2}^{\text{Lin}}$ is the transmission capacity limitation of the power line $b1-b2$. $V_{b1,\text{Max}}^B$ and $V_{b1,\text{Min}}^B$ are the upper and lower limitation of the voltage amplitude of bus $b1$ respectively.

(2) renewable energy operation characteristics constraints

The renewable energy operation characteristics constraints are the operation requirement that the renewable energy should meet in the distribution network. In addition to the operation characteristics of reactive power support capacity introduced in this paper, the clearance results of renewable energy also need to meet the output range constraints in the actual transaction clearance. Generally, the clearance results should not exceed the predicted power value, which can be expressed as:

$$P_{\text{re},t}^F \leq P_{\text{re},t}^B$$  \hspace{1cm} (14)$$

where $P_{\text{re},t}^B$ is the clearing results of the power of the renewable energy plant $re$ at the time interval $t$. $P_{\text{re},t}^F$ is the prediction value of the renewable energy plant $re$ at the time interval $t$.

In the actual operation process, it is generally required that the renewable energy in the distribution network should adopt the constant voltage control mode to ensure that the voltage of its connecting nodes is a given value. If it is difficult for renewable energy to maintain the voltage of distribution network nodes by regulating its own reactive power output within the range of reactive power regulation, it will switch to the constant power factor control mode, and optimize and adjust its active power output within the range of reactive power regulation, so as to only maintain the voltage level.

3.3. Clearing method

In order to consider the reactive power regulation capability of renewable energy in detail and avoid the introduction of a large number of state variables, which would lead to difficulties in solving the model, this paper proposes a distribution network transaction clearing method based on the reactive power relaxation of renewable energy. In fact, the process is shown in Figure 2. The main characteristic of this clearing process is that all renewable energy sources are firstly set to the constant voltage control mode. The transaction clearing model of distribution network based on reactive relaxation is constructed without considering the limitation of reactive power output capacity of renewable energy. According to the clearing result, the existence of renewable energy reactive power output exceeding limit is determined. The over-limit renewable energy was changed into the constant reactive power control mode, and the solution was resolved until the clearance results satisfying the requirements were obtained.
4. Case study
A case study is used to verify the validity of the proposed method based on the REDS-32 buses system. There are three renewable energy sources in the case and their basic information is shown in Table 1.

| name  | bus | active power adjustment range/MW | reactive power adjustment range/MVar |
|-------|-----|----------------------------------|---------------------------------------|
| Re1   | 10  | [0,30]                           | [-10,10]                              |
| Re2   | 15  | [0,20]                           | [-8,8]                                |
| Re3   | 26  | [0,40]                           | [-15,15]                              |

By using the clearing algorithm proposed in this paper, the process of clearing converges and outputs the final optimal clearing result after 2 rounds of iteration. The final optimization results are shown in figure 3.

In order to further illustrate the actual value of the transaction clearing method shown in this paper, the difference between the optimization results of the traditional transaction clearing method and the method proposed in this paper is compared. As shown in Table 2, the clearing results in this paper are basically the same as the traditional algorithm, but the actual calculation is greatly reduced, which indicates that the method proposed in this paper has high computational efficiency and is more suitable for practical application.
Table 2. Basic information of renewable energy sources

|                          | Optimal solution/$ | Computation time/s |
|--------------------------|--------------------|--------------------|
| This paper               | 2345               | 36                 |
| Traditional method       | 2368               | 397                |

5. Conclusion

In order to solve the problem of transaction clearing in the distribution network market after a large number of renewable energy sources are connected, the reactive power support characteristics of renewable energy are studied in this paper, and a distribution network transaction clearing method considering the reactive power support capability of renewable energy is proposed. Due to the careful consideration of the reactive characteristics of renewable energy, the transaction clearing results are closer to the actual needs, which play an important role in improving the operation efficiency of distribution network and ensuring the safe and stable operation of power network.

Acknowledgments

This work was supported by the Guangdong Power grid information project (No. 037800HK42180074).

References

[1] Garces A.(2016) A Linear Three-Phase Load Flow for Power Distribution Systems. IEEE Transactions on Power Systems, 31: 827-828.
[2] AlHajri M. F., El-Hawary M. E.(2010) Exploiting the Radial Distribution Structure in Developing a Fast and Flexible Radial Power Flow for Unbalanced Three-Phase Networks. IEEE Transactions on Power Delivery, 25: 378-389.
[3] Ding T., Liu S., Yuan W., Bie Z., Zeng B.(2016) A Two-Stage Robust Reactive Power Optimization Considering Uncertain Wind Power Integration in Active Distribution Networks. IEEE Transactions on Sustainable Energy, 7: 301-311.
[4] Mei Q., Jain P. K., Hua J.(1999) Modeling and performance of a power distribution system for hybrid fiber/coax networks. IEEE Transactions on Power Electronics, 14: 273-282.
[5] Baxevanos I. S., Labridis D. P.(2007) Software Agents Situated in Primary Distribution Networks: A Cooperative System for Fault and Power Restoration Management. IEEE Transactions on Power Delivery, 22: 2378-2385.
[6] Yuan H., Li F., Wei Y., Zhu J.(2018) Novel Linearized Power Flow and Linearized OPF Models for Active Distribution Networks With Application in Distribution LMP. IEEE Transactions on Smart Grid, 9:438-448.
[7] Koraki D., Strunz K.(2018) Wind and Solar Power Integration in Electricity Markets and Distribution Networks Through Service-Centric Virtual Power Plants. IEEE Transactions on Power Systems, 33: 473-485.
[8] Li Z., Wu W., Zhang B., Tai X.(2020) Analytical Reliability Assessment Method for Complex Distribution Networks Considering Post-Fault Network Reconfiguration. IEEE Transactions on Power Systems, 35:1457-1467.
[9] Tang Z., Hill D. J., Liu T.(2019) Fast Distributed Reactive Power Control for Voltage Regulation in Distribution Networks. IEEE Transactions on Power Systems, 34: 802-805.
[10] Chen S. X., Foo Y., Eddy S., Gooi H. B., Wang M. Q., Lu S. F.(2015) A Centralized Reactive Power Compensation System for LV Distribution Networks. IEEE Transactions on Power Systems, 30:274-284.