Research on “source-grid-load” coordination operation index system of ADN

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Abstract. With the large-scale access of distributed generation (DG), the passive distribution network with one-way flow has been replaced by the active distribution network (ADN) with two-way flow. The existing research of grid interaction does not consider the problem as a whole. Rather, it only aims at one partial aspect, for instance, source-grid interaction or user interaction. Moreover, former researchers haven’t set an accurate and comprehensive index system to evaluate the level of interaction. The “source-grid-load” index system of active distribution network was established from four aspects of safety, economy, environmental and coordination, and the specific calculation method of every index was given as well. The index system can promote understanding of AND.

1. Introduction

With the full development of smart grid construction and the large-scale access of distributed generation (DG), the traditional distribution network has active characteristics. The ADN has undergone profound changes in the aspects of planning, operation, control, and protection. The ADN is a distribution network with the ability to control various distributed energy sources (e.g. photovoltaic panels, wind generators, micro-turbines and small hydro-powers), and connects the power supplies and customer requirements effectively through active control and management. The ADN can improve the number and operation efficiency of DG, increase the acceptance capacity of distribution network to renewable distributed energy, improve the utilization rate of distribution network assets and improve the power quality and power supply reliability.

The ADN planning is different from the traditional distribution network planning. The traditional distribution network planning generally follows the steps of "load forecasting-power planning-network planning", however, the emergence of DG will lead to greater uncertainty in power system load forecasting and operation and affect the distribution network planning. Therefore, the ADN planning has to consider the coordinated interaction between DG and distribution network frame and load demand.

The existing research of grid interaction does not consider the problem as a whole. And, it only aims at one partial aspect, for instance, source-grid interaction or user interaction. Moreover, former researchers haven’t set an accurate and comprehensive index system to evaluate the level of interaction.

Firstly, the paper explains the meaning of "source-grid-load" coordination, then, establishes the ADN planning system by considering source-grid coordination, grid-load interaction and source-load interaction. At last, the “source-grid-load” index system of ADN is established from three aspects of
coordination, safety and economy, and the specific calculation method of every index is given as well. The system has important guiding significance to the planning and construction of ADN.

2. The theory system of “source-grid-load” coordination

The essence of “source-grid-load” coordination is an operation mode that can maximize the utilization of resources. The source, grid and load form a whole, and it is of great significance to study the coordination and interaction among them to promote the development of ADN.

![Fig.1 The “source-grid-load” coordination system](image)

2.1 The source-grid coordination

In the below paragraph, the source-grid coordination is mainly reflected in two aspects:

1. Under the background of ADN and according to the demand of power demand balance, large scale and various kinds of DGs should be applied reasonably;

2. Cooperating new energy generation with conventional energy sources such as thermal power generation and hydroelectric power generation.

The development of source-network coordination technology will greatly promote the ability of renewable energy to be predictable, controllable and dispatchable. Consideration of the “source-grid” coordination in distribution network planning, and it means connecting as many DGs as possible within the maximum tolerance of the power grid.

2.2 The grid-load interaction

The requirements of different loads for power supply reliability are also different, and load behaviour and its characteristics largely determine the economy and security of power grid operation. With the development of demand side management technology, encouraging users to take the initiative to cut peaks and fill valleys through electricity price policies, becomes an important measure to improve the safe and stable operation of power system. Interruptible loads are emergency backup power generation resources that can be control by the power grid and they are another forms of backup. When the reserve capacity is insufficient, the needed power can be effectively replenished, thereby ensuring safe and reliable operation of the power grid. Besides, DG, electric vehicles, micro-grid, energy storage equipment, etc. are more and more widely used. The new flexible loads have the characteristics of both power generation and energy storage, can achieve two-way interaction with the power grid, and participate in power grid regulation and become black-start power supplies.

2.3 The source-load interaction

The widely distributed multi-sources and loads are important components of the future power grid. Both the power supply side and the load side can be used as schedulable resources. Controllable devices such as electric vehicles and energy storage on load side can participate in active regulation of
power grid, and demand side resources such as industrial loads, commercial loads, etc. can respond to grid demand in real time and participate in power supply and demand balance. Through effective management mechanisms, flexible loads will become important means to balance the power fluctuations of intermittent new energy.

There are two meanings to study the interaction between sources and loads in distribution network:
(1) The power generated by DG is used as much as possible for the load;
(2) The power consumed by the load comes from DG as much as possible.

3. Formatting the text
The goal of “source-grid-load” coordination operation is to make the ADN run in a safer, more economical and more environmentally friendly state. In addition, the established indexes should reflect the operation effect of source, grid and load, so the index system is also needed to reflect the level of “source-grid-load” interaction.

According to the construction principle of the evaluation index system, the Principal Component Analysis (PCA) is used to choose reasonable indexes and the Analytic Hierarchy Process (AHP) is used to establish the evaluation index system from four perspectives: safety, economy, environmental friendly and coordination. The “source-grid-load” coordination operation index system of ADN is shown in Fig.2.

![Fig.2 The Index System](image)

3.1 Safety indexes A
(1) Voltage qualified rate $A_1$
The index is the proportion of the number of nodes in the limited range of voltage to the total number of nodes.

$$A_1 = \frac{m_{nq}}{m_{ns}} \times 100\%$$  \hspace{1cm} (1)

In the formula, $m_{nq}$ refers to the number of nodes with qualified voltage in the network, and $m_{ns}$ refers to the total number of nodes in the network.

(2) Line overload rate $A_2$
The index is the proportion of the number of overloaded lines to the total number of lines.

$$A_2 = \frac{m_{lo}}{m_{lx}} \times 100\%$$  \hspace{1cm} (2)

In the formula, $m_{lo}$ is the number of overloaded lines in the network (the line current reaches more than 80% of the rated value).

(3) N-1 pass rate $A_3$
It includes two parts: N-1 pass rate of transformer and N-1 pass rate of line.
(a) N-1 pass rate of transformer $A_{31}$
The index is the proportion of the number of transformers satisfying N-1 to the total number of transformers.

\[ A_{31} = \frac{m_{Tq}}{m_{Ts}} \times 100\% \]  

(3)

In the formula, \( m_{Tq} \) is the number of transformers satisfying the N-1 principle in the network, \( m_{Ts} \) is the total number of transformers in the network.

(b) N-1 pass rate of line \( A_{32} \)

The index is the proportion of the number of lines satisfying N-1 to the total number of lines.

\[ A_{32} = \frac{m_{lq}}{m_{ls}} \times 100\% \]  

(4)

In the formula, \( m_{lq} \) is the number of lines satisfying the N-1 principle in the network, and \( m_{ls} \) is the total number of lines in the network.

(4) Power supply reliability rate \( A_4 \)

The power supply reliability rate reflects the reliability of the system.

\[ A_4 = \frac{m_{te}}{m_{ts}} \times 100\% \]  

(5)

In the formula, \( m_{te} \) is the effective generation time, and \( m_{ts} \) is the statistical period time.

3.2 Economic indexes \( B \)

(1) Peak-valley difference rate \( B_1 \)

The greater the difference between the peak and the valley, the greater the pressure of the system to cut the peak and fill the valley, and the less economical it is. The specific calculation method is as follows.

\[ B_1 = \frac{m_{p/v}}{m_{ml}} \times 100\% \]  

(6)

Where, \( m_{p/v} \) is the peak-valley difference, and \( m_{ml} \) is the maximum system load.

(2) Average line loss rate \( B_2 \)

Average line loss rate is used to reflect the overall line loss of the system. It can be calculated by averaging the line loss rate of all lines. The specific calculation method is as follows.

Firstly, calculate the line loss rate of a line.

\[ \alpha_i = \frac{\Delta I}{P_i} \times 100\% \]  

(7)

Where, \( \Delta I \) is the line loss of the \( i \)th line, and \( P_i \) is the load of the \( i \)th line. Then the average line loss rate can be calculated.

\[ B_2 = \frac{1}{M} \sum_{i=1}^{M} \alpha_i = \frac{1}{M} \sum_{i=1}^{M} \left( \frac{\Delta I}{P_i} \times 100\% \right) \]  

(8)

(3) Average power supply radius of line \( B_3 \)

The index is the proportion of the sum of the power supply radius of line to the total number of lines.

\[ B_3 = \frac{\sum_{i=1}^{N_L} R_i}{N_L} \]  

(9)

Where, \( R_i \) is the power supply radius of the \( i \)th line, and \( N_L \) is the total number of lines.

3.3 Environmental indexes \( C \)

(1) Energy utilization efficiency \( C_1 \)

Different energy sources are unevenly distributed over time, by rationally allocating the utilization time of different energy sources, can improve the overall system energy utilization efficiency.

The calculation formula for energy utilization efficiency is
\[ C_1 = \sum_{i=1}^{k} (a_i \times \eta_i) \]  

(10)

In the above formula, \( C_1 \) is energy utilization efficiency, \( i \) is the \( i \)th power supply, \( k \) is the total number of power supplies, \( a \) is the weight of different energy sources in the calculation, \( \eta_i \) is the energy utilization efficiency of every power supply.

(2) DG permeability \( C_2 \)

The clean and environmental protection of ADN is mainly reflected in the effective use of DG and can reduce the network loss by reasonable access.

The DG permeability means:

\[ C_2 = \sum_{i=1}^{n} \frac{W_i}{W_s} \]  

(11)

In the formula, \( W_i \) is the annual power generation of \( i \)th DG, \( W_s \) is the annual power generation of the whole system.

(3) EV permeability \( C_3 \)

Electric vehicles (EVs) achieve zero emissions of vehicle exhaust and make a great contribution to the improvement of the environment.

The EV permeability means:

\[ C_3 = N \cdot \frac{P_{EV}}{P_{max}} \]  

(12)

In the formula, \( N \) is the number of EVs that the system can access simultaneously, \( PEV \) is the charging power of EV, \( P_{max} \) is the maximum load power of power grid.

3.4 Coordination indexes \( D \)

(1) Transformer load coordination \( D_1 \)

Transformer load coordination can be expressed as:

\[ D_1 = \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{m_i} (\eta_{ij} - \eta_{Tavg})^2 \]  

(13)

In the formula, \( n \) is the number of transformer substations, \( m_i \) is the \( i \)th transformer of the \( m \)th substation, \( \eta_{ij} \) is the load rate of the \( ij \)th transformer, \( \eta_{Tavg} \) is the average load rate of all transformers.

(2) Line load coordination \( D_2 \)

Transformer load coordination can be expressed as:

\[ D_2 = \frac{1}{h} \sum_{i=1}^{h} (\eta_i - \eta_{Lavg})^2 \]  

(14)

In the formula, \( h \) is the number of the transmission lines, \( \eta_i \) is the load rate of the \( i \)th transmission line, \( \eta_{Lavg} \) is the average load rate of all lines.

(3) DG utilization \( D_3 \)

The formula for calculating the index is:

\[ D_3 = \frac{W_{Du}}{W_{Do}} \times 100\% \]  

(15)

In the formula, \( W_{Du} \) is the used electricity of DG, \( W_{Do} \) is the output electricity of DG.

4. Appendices

In this paper, the specific meanings of "source network load" coordination are expounded from the perspectives of source-grid coordination, grid-load interaction and source-load interaction, and the "source-grid-load" index system of active distribution network is established from four aspects of safety, economy, environmental and coordination, and the specific calculation method of every index is given as well. The index system can be used for comprehensive evaluation of the ADN and it has great practical value.
The distribution network planning system with DG considering “source-grid-load” coordination established could guide the construction of distribution network planning with DG and promote the improvement of the comprehensive effectiveness of smart grid.

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