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Framework for Future Smart Grid Operation and Control with Source-Grid-Load Interaction

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Abstract: In order to meet the challenges in the future smart grid operations, this paper presents a new concept of Source-Grid-Load interactive operation and control, which provides new ideas and effective technical means for the future smart grid operations. The Source-Grid-Load interactive operation consists of complementarities of power supply sources, coordination between power supply sources and power grid, interactions between grid and load, as well as interactions between power supply sources and system load. It aims to improve energy balance and dynamic power balancing ability among the power supply sources, load and power grid more economically, efficiently and safely. Based on analyses of the complex interaction characteristics of the future grid, this paper proposes a theory and technology framework for the interactive and flexible system operation, puts forward that in-depth study shall be made to understand the Source-Grid-Load complex interaction characteristics, form the interaction modeling method, develop the technologies of energy balance and security analysis, and break through the technology of the Source-Grid-Load coordinative control in the environment of wide area complex interaction. It provides systematic basis for the flexible and interactive operation and control in the future smart grid, and helps to push the development of power system scheduling from the unidirectional mode 'generation following the load' to the smart and interactive mode of Source-Grid-Load.

1. INTRODUCTION

The development pattern of smart grid will be greatly changed in the future. From the perspective of power generation, 'Flexible Power Plants' with friendly regulating ability and characteristics will become an important sources of power supply. From the perspective of power consumption, since electric loads are becoming more flexible and controllable, they can become one of means to balance the fluctuations of power supply. Breakthroughs in distributed generation and energy storage technologies will lead to a revolutionary change in the power consumption. From the perspective of power grid, the grid must have a flexible and open access capability and an adaptable adjustment ability to support Source-Grid-Load interaction. Therefore, Source-Grid-Load interaction is a significant mean to cope with energy resource structure change for the future power system, and is also an inevitable trend of the rapid development of power grid (Yao Jianguo et al., 2012).

In smart grid development process, we are facing three major challenges: 1) consumption of large-scale centralized and distributed renewable energy; 2) 'plug and play' and random connections of electric vehicles, energy storage and high penetration of distributed generation resources; and 3) safe and efficient operation of the future smart grid in the premise of open interactive operations. In the future, there will be a large amount of renewable energies (centralized/distributed), charge-discharge facilities (energy storage/electric vehicles) and controllable loads, which will lead to a change in Source-Grid-Load interaction. In addition to the existing interaction between regular sources and grid, interactions might exist between sources and load, between power grid and load, between regular sources and renewable sources, and among different renewable sources. It results in a very complex interactive behaviour in power system. Operation, control and management in the future power grid will face significant challenges under the source-Grid-Load interactive environment. First of all, the increased uncertainties, the high degree of randomness and the bidirectional power flows change the conventional characteristics of system operations, which the power generation is highly controllable and the daily changes of power consumption is predictable. Secondly, with the open access of grid and the interactive operation between load and grid, the connections of the massive plug-and-play distributed power supplies and the random load response bring a huge challenge to power system operations. Thirdly, how to effectively achieve an orderly interaction between the bulk power grid and the distributed grids, and how to balance the distributed resources and the centralized generating resources will also become important challenges for the future grid operations.

The related researches focus on the uncertainty analysis methods of power system (Kang Chongqing et al., 2011; Zhao Junhua et al., 2010), random power flow (Zhang Pei et al., 2004; Dong Lei et al., 2012), renewable energy integration technologies (Willett Kempton et al., 2010; M.

Ma et al., 2010), the interaction between distributed power generation/microgrid and bulk power grid (Lasseter R H et al., 2006; Xin H et al., 2011), the interaction between electric vehicles/energy storage and power grid (Christophe G et al., 2009; Qian Kejun et al., 2010), as well as demand response technology (Duncan S. Callaway et al., 2011; M.Klobasa, 2010) [17-18]. These studies focus on solving certain key technical problems that the grid operations are facing at current stage. There lacks of an overall thinking and systematic research on the impact of Source-Grid-Load interaction on power grid operation and control.

In this paper, the complex interaction characteristics of the future grid are analysed. A framework of the smart grid Source-Grid-Load interactive operation and control is proposed from the perspective of system operation and control, which includes the basic theory, the operational characteristics, the steady-state analysis , the energy balancing methods, the dynamic security analysis and the coordinated control technology, etc.. It lays a foundation for the further theoretical and technical studies of Source-Grid-Load interactive operation and control.

2. ANALYSES ON COMPLEX INTERACTION CHARACTERISTICS OF THE FUTURE GRID

Traditionally the mode of t power system operation control is 'generation following the load'. It does not have much interaction. The future grid is a complex system with coordination between new energies and traditional energies, as well as interaction between flexible loads and traditional loads. There are various coupling relationships and interactions among 'Source', 'Grid' and 'Load'. Compared with the traditional power system, interactive operation characteristics of the future grid will be more complex.

2.1 Variety and Flexibility of Interactive Body

The future grid has the characteristic of multi-directional interaction among 'Source', 'Grid' and 'Load'. Besides the conventional power supply sources, there are also intermittent power supply sources, pumped storage power plants, large storage facilities and other flexible power supplies, and the proportion of flexible sources is gradually increasing. Besides the traditional types of load, there are also electric vehicles, load with small intermittent power supplies and/or small controllable power supplies, small storage devices, interruptible loads and other flexible controllable loads, and the proportion of flexible loads is gradually increasing. With the 'Source', 'Grid' and 'Load' being the body of interaction, there are various interactive modes such as complementary between source and source, coordination between source and grid, interaction between grid and load, as well as interaction between source and load. With the rapid development of new theories, technologies and materials, 'Source', 'Grid' and 'Load' have flexible characteristics. Random renewable energies and other flexible sources such as hydropower, gas turbines and pumped storage will be predictable and adjustable. The traditional controllable load and micro-grid, energy storage, electric vehicles, demand response will be developed into flexible load that is suitable to power grid regulation, and there are other flexible controllable devices like FACTS in power grids.

2.2 The Multiple Time and Space Scale Characteristics of Interactive Behaviour

The complex Source-Grid-Load interactive operation shows obvious characteristics of multiple time-varying. The relative change rate of wind power in any given period of time can be described as

$$\lambda_n = (P_i / P_R)*100\% = [(P_{(t+s)} - P_t) / P_R]*100\% \qquad (1)$$

where P_t, P_{t+s} represent wind power output at time t and $t+s$ respectively, P_i represents wind power fluctuation from t to $t+s$, P_R represents wind power capacity, and λ_n is the relative change rate of wind power.

The wind power output data in North China are sampled at 5 seconds, 5 minutes and 60 minutes respectively through the whole year 2012. As shown in Table 1, the fluctuation of renewable energy varies with different time scales. The wind power output does not change substantially within 5 seconds, but its fluctuation in one hour will become significantly. The number of demand-side resources is large and the distribution is wide. Because of their different electricity consuming characteristics, the response times are also different (Zhang Qin et al., 2008). According to the different characteristics of supply-side and demand-side resources, it needs to consider comprehensively in the time scale for power system planning and day-ahead, hour-ahead, real-time scheduling.

Table 1. The fluctuation characteristics of wind power varies with different time scales

Time scale	the maximum forward fluctuation	the maximum reverse fluctuation
5s	0.24%	-0.26%
5min	1.68%	-3.57%
1h	12.1%	-12.5%

In the wide-area space scale, there are correlative and complementary characteristics between renewable energies at different locations. The stronger the correlative characteristic is, the worse the complementary characteristic will be, and vice versa. The correlative and complementary characteristics between renewable energies can be evaluated quantitatively by defining the correlation coefficient and complementarity coefficient.

Suppose the wind power output fluctuation P_i is a normal random process, and random variables X, Y represent the power output sequences of two wind farms. The correlation coefficient between wind farms can be calculated by equation (2). The closer that the correlation coefficient is to 1, the more similar changing trend the two farms have, and the closer that the correlation coefficient is to -1, the more opposite changing trend they have.

$$\rho_{x,y} = \frac{\frac{1}{n}\sum_{i=1}^{n}(P_{xi}-\mu_x)(P_{yi}-\mu_y)}{\sigma_x\sigma_y} \quad (2)$$

where P_{xi}, P_{yi} represent wind power fluctuations, μ_x, μ_y represent mathematical expectations of wind power fluctuation, and σ_x, σ_y represent variances of wind power fluctuation.

The North China power grid is composed by power grids of Shanxi, South Hebei, Jing-Jin-Tang and Shandong, and it connects with Inner Mongolia Power Grid, Northeast China Power Grid and Central China Power Grid, whose power grid structure is shown in Fig. 1. The average correlation calculation results of wind power output at 1h interval of North China in 2012 are shown in Table 2. The correlation is divided into three levels according correlation coefficient: if | r | <0.4, it is a low linear correlation; if 0.4 <| r | <0.7, it is a significant correlation; if 0.7 <| r | <l, it is a highly linear correlation.

Table 2. The average correlation of wind power output of North China at 1h interval in 2012

correlation coefficient |r|	South Hebei	Jing-Jin-Tang	Shandong	Shanxi	Inner Mongolia	North China
South Hebei	1	0.6234	0.4966	0.6793	0.4372	0.7017
Jing-Jin-Tang	0.6234	1	0.3403	0.6481	0.5828	0.8382
Shandong	0.4966	0.3403	1	0.35502	0.2024	0.55752
Shanxi	0.6793	0.6481	0.35502	1	0.5625	0.7594
Inner Mongolia	0.4372	0.5828	0.2024	0.5625	1	0.85090
North China	0.7017	0.8382	0.55752	0.7594	0.85090	1

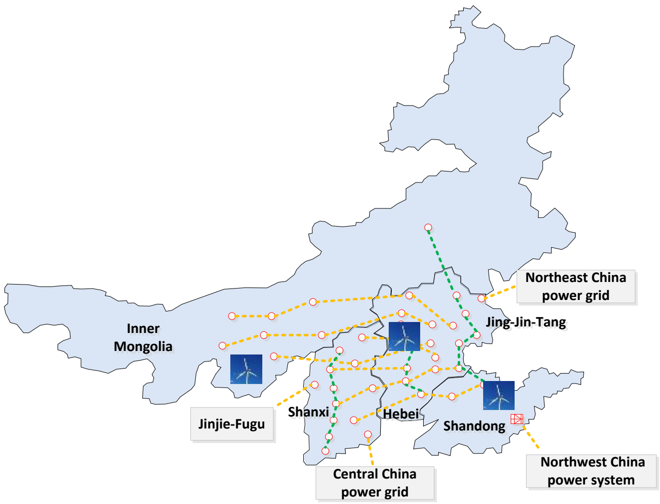


Fig. 1. Power grid structure of North China

2.3 Uncertainty of Interactive Behaviour and Development Trend

The interactive behaviour and its development trend are uncertain because of the randomness and intermittence of renewable energies at power supply side, as well as the autonomy and disorder of flexible load response at the load side. On the one hand, dynamic behaviour of the interactive body is uncertain. Unlike the certainty and controllability of traditional power and load, new energy output and flexible load response will fluctuate in a certain range, and it shows the properties of probability distribution. From the perspective of power supply, large-scale wind and photovoltaic power generation are developed and integrated into power grid. The characteristics of these renewable energies, such as fluctuation, intermittence, anti-peaking and low schedulability, bring serious influence to the security, stability and economic operation of power grid. The power system needs to keep sufficient reserve and peaking capacity, and restricts the intermittent energy output ceiling. It is necessary to coordinate the scheduling among power sources at different types and locations, because the power sources' response time of disturbance is different and their spatial positions of are discrete. From the perspective of power load, flexible load is affected by customer's behaviours. Hence, the load changes are very subjective. System load alters with changes of external environment and electricity prices, which result in a broad uncertainty of flexible load response behaviour in different time and space scales. Also, the characteristics of potential controllable loads, such as energy storage and electric vehicles, when participating in power grid regulation, are very complicated if considering the battery properties and user behaviours. Meanwhile, uncertainty of users' response will also bring great uncertainty to power grid operation due to the demand response is end-user oriented. On the other hand, interactive trend is uncertain. Uncertainty will make interaction developing in either positive or negative trend. The positive interaction can promote new energy consumption, which is conducive to the security and stability. The negative interaction caused by uncertain disorder response may lead to operation condition changes of power system at any time, which will become a new vulnerable spot, and even influence the stability and security of power system operation.

2.4 Complexity of Power Flow Distribution

The randomness of intermittent power output and integration of large-scale distributed power supplies will bring changes to the distribution grid. The characteristic and distribution of power flow will also change due to the crowding effects caused by large-scale electric vehicles' integration, the individual and combined effects of complex load response and the adjustment of power grid structure. The power flow will have features of bidirectional flowing, unbalanced distribution and wide range shifting, which may stimulate the weakness in power system and cause a cascading failure.

The load rate and power flow entropy (Cao Yijia et al., 2011) quantitatively describe the distribution of line flow and its unbalance characteristics. Suppose the maximum active power transmission capacity of line i is $F_i^{\max}$, and the actual power flow of line i is F_i^0, The load rate μ_i of line i is given as,

$$\mu_i = \left| F_i^0 / F_i^{\max} \right| \qquad i = 1, 2, \cdots N_1 \tag{3}$$

where N_1 is the number of lines.

The entropy measures the chaos and disorder degree of a system. There may be several different states in a system. Suppose the probability of state X_i is $P_i(i = 1, 2, ..., m)$, and the entropy of this system is defined as:

$$H = -C \sum_{i=1}^{m} P(X_i) \ln P(X_i) \tag{4}$$

where C is constant and m is the number of states.

When the constant sequence $U = \{U_1, U_2, \cdots, U_j, \cdots U_n\}$ is given, and l_j represents the number of lines with the load rate $\mu_i \in \left(U_j, U_{j+1}\right]$, we can get the probability of line numbers in different load rate interval.

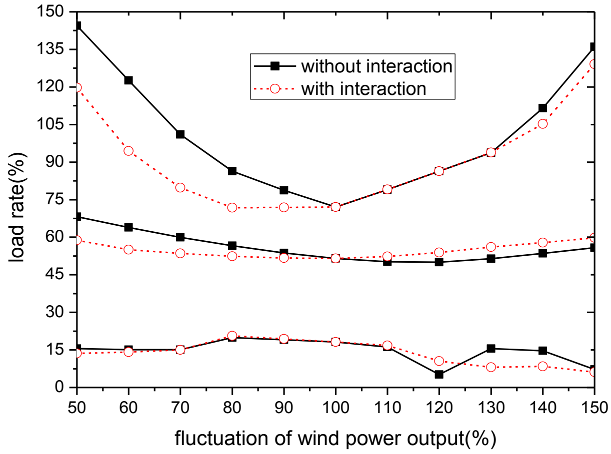
$$P(j) = l_j / \sum_{j=1}^{n-1} l_j \tag{5}$$

In (5), $P(j)$ is the percentage of lines with the load rate $\mu_i \in \left(U_j, U_{j+1}\right]$ in total lines.

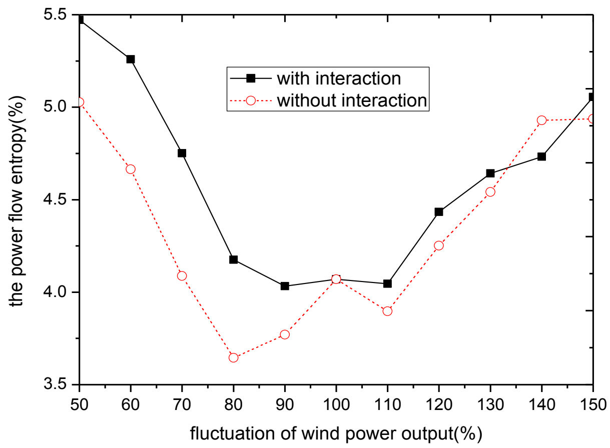
The power flow entropy of power grid can be derived from equation (3)-(5),

$$H = -C \sum_{j=1}^{n-1} P(j) \ln P(j) \tag{6}$$

The load rate and power flow entropy comparisons with and without Source-Grid-Load interaction are shown as in Fig.2. Fig.2 (a) shows that the maximum load significantly decreases when there is an interaction, and it indicates that interaction plays a role in reducing overload of power system. But the load rate with interaction increases sometimes. The comparison of the power flow entropies with interaction and without interaction is described in Fig.2 (b). The results show that power flow entropies with interaction are less than ones without interaction in most cases, and it illustrates that flexible load participated in interaction plays a good role in balancing flow distribution. But the power flow entropies with interaction are higher sometimes, and this means that the flow distribution is more unbalanced when there is an interaction. It follows that the uncertainties of interactive behaviour and development trend make the power flow distribution more complex. The interaction can balance the power flow distribution, but interaction without guidance may cause overload in some lines or local regions and even bring some security concerns. Therefore, it is necessary to guide positive development of interaction through reasonable strategies for dispatching centres, so as to ensure security and stability of power grid.



(a)The load rate comparison



(b)The power flow entropy comparison

Fig. 2. The impacts of interaction on power flow distribution

3. FRAMEWORK OF SOURCE-GRID-LOAD FLEXIBLE INTERACTIVE OPERATION AND CONTROL

According to the complex interaction characteristics analysis, the Source-Grid-Load interaction can enhance the energy balance ability of power system, but also bring great challenges to operation control and scheduling model of the traditional power system. So it is necessary to establish a new theoretical and technical framework for power system operation. The following seven aspects should be studied and developed: characteristic analysis, behaviour modelling of complex interaction, steady-state analysis, energy balance method, dynamic security analysis, coordinated control technology and supporting technology of information and communication under flexible interactive environment, The general theoretical and technical framework of Source-Grid-Load flexible interactive operation and control is shown in Fig. 3.

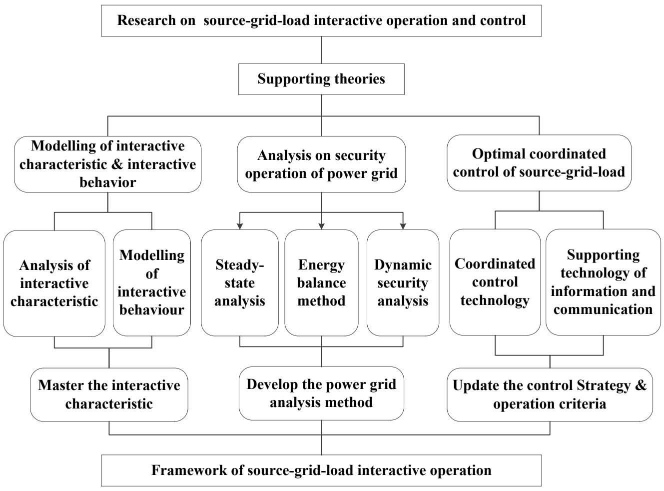


Fig.3. Research framework of Source-Grid-Load interactive operation and control

3.1 Research and Development of Supporting Theories

Research of Source-Grid-Load interactive operation and control involves multiple research fields, such as energy, control, and information. According to the actual demand of the future power system for the complex, diverse and uncertain factors, it is potential to develop and apply some new theoretical tools like system dynamic theory, uncertainty theory, entropy theory, game theory, such that a breakthrough both in the theory and technology can be achieved.

3.2 Complex Interaction Characteristics Analysis

Source-Grid-Load complex interaction characteristics are the base of the interaction modelling, analysis and control. The key research points of complex interaction characteristics are summarized as following.

1) It is essential to study the forms and modes of Source-Grid-Load interaction after integration of large-scale renewable energy and flexible load in the future grid.

2) It is essential to study the correlative and complementary characteristics and the quantitative analysis method between single/multiple renewable energy resources in different locations.

3) It is essential to analyse the power consumption characteristics and response characteristics, and the potential of demand-side resources.

3.3 Modelling Method of Complex Interaction

The interaction behaviour modelling can be divided into two parts: flexible load response modelling and interactive behaviour modelling.

1) Flexible load response modelling. It requires to study multi-agent and multi-objective modelling as well as multi-form and multi-response comprehensive modelling considering the combination of internal and external characteristics changes of the flexible load.

2) Modelling of complex interaction. The Source-Grid-Load interaction is very complex. Different modelling methods, such as the hybrid modelling method, the random probability modelling methods and the self-adaptive hierarchical modelling method should be taken into account.

3.4 System Steady-State Analysis in Flexible Interactive Environment

In Source-Grid-Load interactive environment, the response characteristics and interaction patterns among 'Source', 'Grid' and 'Load' are more complex than in the traditional power grid, and the uncertainty will become more obvious and more enhanced, which will lead to apparent randomness and fluctuation of power flow distribution. So the new power flow and contingency analysis algorithm considering uncertainty and interactive process should be studies.

3.5 System Energy Balance Methods in Flexible Interactive Environment

The Source-Grid-Load interaction changes the energy balancing mode of 'generation following load' in traditional power system. How to achieve a dynamic energy balance of power system in the uncertain environment is an urgent problem to be solved. The energy balancing control for the future power system needs to consider many factors such as the wide-area complementary characteristics among various sources, the schedulable characteristics of flexible load as well as the security constraints of power grid.

3.6 System Dynamic Analysis in Flexible Interactive Environment

In the interactive process, uncertainties in both 'Source' and 'Load' sides will increase the randomness of disturbances' occurrence. The inertia of some local grids may decrease with the widespread use of power electronic devices in the power system. It changes the system dynamic stability characteristics. So some special issues need to study further.

3.7 Supporting Technology of Information and Communication in Wide-Area Interactive Environment

The supporting technology of information and communication in wide area is the foundation of Source-Grid-Load interactive control. The networking modes and bidirectional transmission protocol of sampled data should be established based on the transmission characteristics of massive data in interactive environment. Closely integrated with intelligent computing techniques, such as cloud computing and fuzzy recognition, the massive data can be handled, and then the data sharing and intelligent control can be achieved.

3.8 Coordinated Control Strategy and Technology of Flexible Interaction

Rapid increase of the number of interactive bodies, uncertainties of intermittent energy operation and flexible response characteristics of distributed controllable load all increase the complexity of power grid operation. Coordinated control strategies and technologies of flexible interaction should be studied to achieve the orderly interaction among 'Source', 'Grid' and 'Load'. Some key technologies including: tie-line power balance control technologies in interaction environment, multi-agent coordinated control technologies and interactive coordination technologies between massive distributed autonomous control and centralized optimal control.

4. CONCLUSIONS

Flexibility, controllability, and interaction are the three trends of the future smart grid, while the Source-Grid-Load interactive operation is the core of the future system operations. The Source-Grid-Load interactive operation brings great changes to the future power system operations. It is urgent to break through the current operation control mode, and establish a new framework to guide the researches on control theory and technologies for the flexible Source-Grid-Load interactive operation. Aiming at the requirements of theory, analysis and control of Source-Grid-Load, this paper explores the complex interaction characteristics of Source-Grid-Load and builds the control theory and technology framework of smart grid Source-Grid-Load flexible interactive operation. Interactions among power supply sources, power grid and load can greatly enhance the dynamic balance ability, to achieve the optimal allocation of bulk power resources, and to improve energy efficiency.

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